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Results of the Groundwater Geochemistry Study on Saturna Island, British Columbia

Final Report

Prepared by:

D.M. Allen and M. Suchy
Department of Earth Sciences
Simon Fraser University
Burnaby, B.C. V3Y 2L4

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EXECUTIVE SUMMARY

Groundwater supplies the majority of potable water in many coastal communities and islands in British Columbia. Consequently, more attention is being paid to its quality and quantity, and to the processes that potentially threaten this valuable resource. This study benchmarks the current groundwater chemistry on Saturna Island, characterizes the general evolution of groundwater on the island, and provides data for future studies involving the chemical evolution of groundwater on the Gulf Islands.

Water samples were collected during the summers of 1997 and 1998 from water wells volunteered by local residents and from other natural water sources (springs, surface waters, etc.) as part of a research project funded in part by the Saturna Island Local Trust and Simon Fraser University. Water samples were analyzed for dissolved ionic species (i.e., metals and common anions), and were interpreted in the context of the local geology in order to provide information on the chemical character of groundwater (including the spatial distribution of dissolved metals and anions), the evolution of groundwater within different flow regions, and the location of recharge and discharge areas.

Groundwater on Saturna Island is recharged locally, focused around areas of high elevation corresponding to Mt. Fisher, Mt. Warburton, Mt. David and Mount Elford. The relatively immature chemical composition of many well waters (calcium-bicarbonate type water) situated at lower elevations suggests that recharge also occurs over a significant portion of the island, and is not restricted to high elevation. However, limited recharge occurs on East Point as evidenced by the large number of wells with measured high salinities. Many groundwaters have undergone extensive cation exchange, a process whereby sodium replaces calcium during and following the dissolution of calcite. It is suggested that groundwater flow through fractured mudstone units may be the cause for the high occurrence of cation exchange. Mature groundwaters, characterized by higher concentrations of chloride, are prevalent throughout the island. These

mature groundwaters result from mixing between the Na-rich groundwater and saline groundwater that is situated at depth and that corresponds with the freshwater-saltwater interface beneath the island. In addition, saltwater intrusion is evident in a number of wells and is characterized by immature waters mixing with seawater. A few wells in the East Point area and other isolated wells situated near the coast show this type salinization, and suggest that saltwater intrusion may be prevalent in that area. In past years, several wells were abandoned in the Lyall Harbour area, likely as a result of saltwater intrusion.

ACKNOWLEDGMENTS

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The following students are also recognized for their contributions to the chemical sampling: Daron Abbey (M.Sc. graduate, SFU) and Mario Bianchin (B.Sc. graduate, SFU). The geological information was supplied by Dr. Peter Mustard (Earth Sciences, SFU).

To the residents of Saturna Island, thank you. Without your valued cooperation the collection of such a large number of samples would have been difficult. It is your participation in this project that allowed us to collect and analyze the data obtained from your wells. This research could not have been done without your support.

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1.0 INTRODUCTION

1.1 Background

Saturna Island is the most eastern and southern of the Canadian Gulf Islands, and is situated immediately north of the international border near the southern end of the Strait of Georgia. The island is approximately halfway between Vancouver and Victoria, and can be accessed by pleasure craft, seaplane, or provincial ferry from Schwartz Bay on Vancouver Island and from Tsawwassen on the mainland. Inhabited islands surrounding Saturna include the Pender Islands to the southwest, Mayne Island to the northwest (Figure 1), and the U.S. San Juan Islands to the southeast. Tumbo Island to the north is a small uninhabited island that is being considered by the Provincial Government of British Columbia for a Provincial Park (Figure 2). Saturna Island is 31 km^2 in area and is extensively developed along several segments of shoreline. It sustains a population of approximately 315 residents year round, although this figure inflates during the summer as part-time residents and visitors arrive. Other Gulf Islands such as Saltspring, Mayne and Galiano have populations of 9240, 997 and 900, respectively (Canada Census, 1996).

Saturna Island, as with many other Gulf Islands, derives its potable water primarily from groundwater. For the most part, groundwater supplies are derived from wells completed in fractured sedimentary rock aquifers, although surficial sand and gravel deposits accessed by shallow wells and natural springs provide potable water in some local areas. Similar to the other islands, fresh potable water is a scarce commodity in some areas of Saturna Island, and several residents practice strict water conservation. As well, water levels are reduced substantially (as indicated by the occurrence of dry wells) in some areas during the summer months when precipitation is low.

Groundwater quality on many of the Gulf Islands and the San Juan Islands to the south is extremely variable and is affected locally by high salinity. Previous

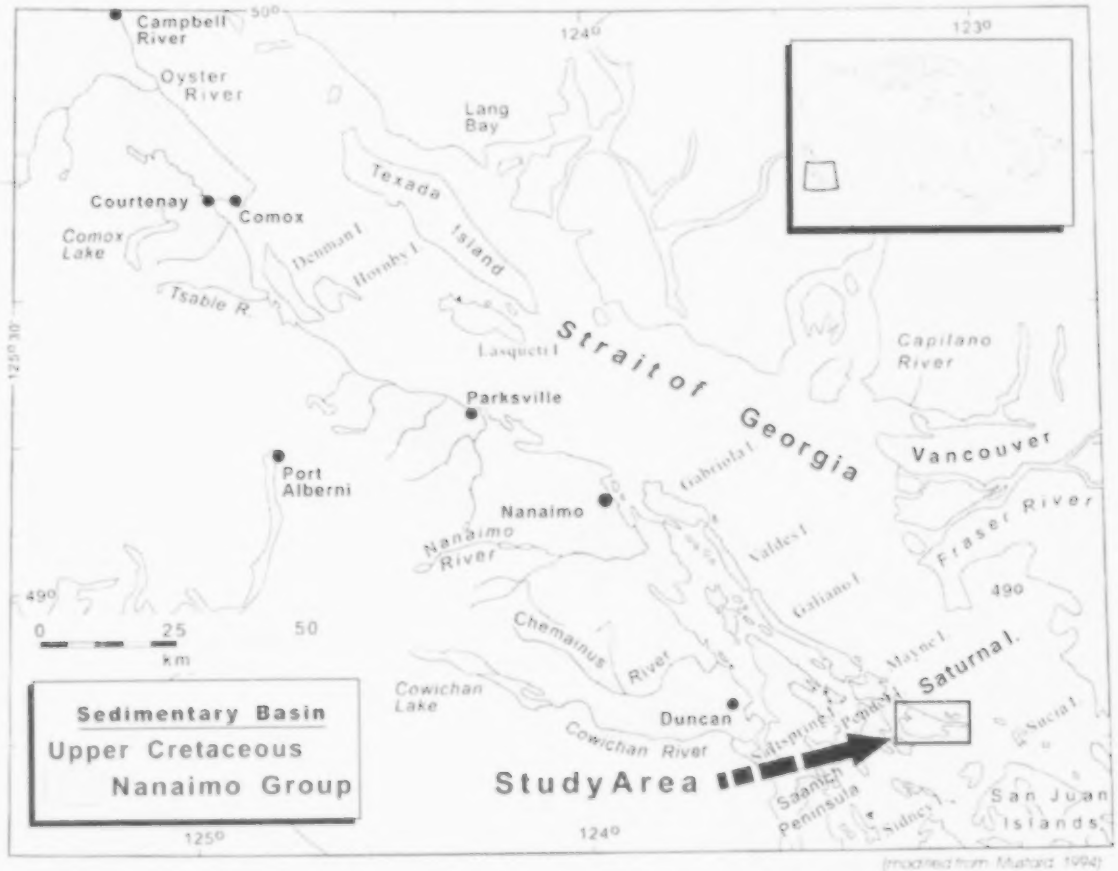


Figure 1: Regional setting of the Nanaimo Group and location of Saturna Island

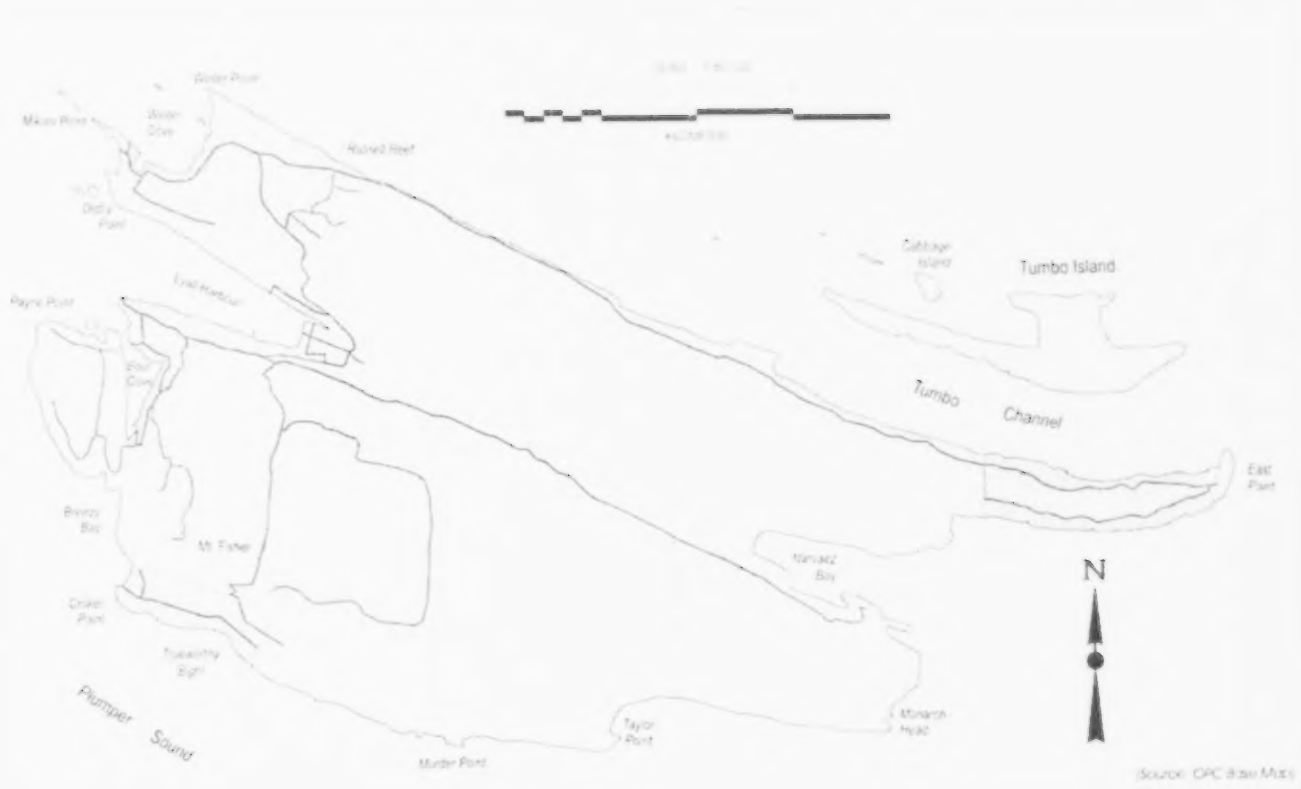


Figure 2: Property boundaries and road map, Saturna Island

studies on Mayne Island and Saltspring, and concurrent studies of water chemistry on Hornby Island (Allen and Matsuo, 2001) indicate significant variability in groundwater salinity. By definition, salinization is the increase of total dissolved solids (TDS) in groundwater due to the interaction with its surrounding material over time (Richter and Kreitler, 1993). All naturally occurring groundwater contains dissolved minerals that contribute to varying degrees of salinity. However, recent increases in the reported number of cases of groundwater deterioration, particularly to the south in the San Juan Islands, suggest that other processes such as saltwater intrusion may be occurring in many coastal areas and islands. Consequently, water quality variations may be more complex on the Gulf Islands than originally anticipated.

1.1.1 Understanding Groundwater Resources of Islands

The development of islands, which rely almost exclusively on groundwater as a supply of potable water, necessitates an evaluation of the long-term sustainability of groundwater resources. Sustainability of the resource is dependent upon a number of factors including the amount of recharge that is received annually by the aquifers, the geological and topographic complexity of the island, and the water use patterns. While the annual seasonal precipitation for Saturna Island is similar to Victoria and averages about 800 mm/year, the summer months are generally much drier. Therefore, consideration must be given to the sustainability of the resource, particularly over the summer months.

Typically, only a portion of the total amount of rainfall infiltrates the subsurface. Estimates of recharge derived for many of the Gulf Islands are approximately 20%, although spatial variability can be expected on the basis of topography and geology. Nevertheless, the relatively low values of recharge present a potential problem, particularly to those areas that receive relatively little recharge or where significant volumes of groundwater are extracted.

Most natural hydrogeological systems maintain a balance between the amount of recharge, the amount of discharge and the amount of water retained in storage. If no groundwater is extracted, then the system is generally in dynamic equilibrium (climate factors aside) and water input equals water output. On an island, water input (recharge) is normally limited to the island surface itself (i.e., there are no external sources), and output is to the ocean, surface streams, rivers and lakes.

Changes in the hydrologic balance due to new or enhanced development may cause changes in the quality and quantity of available potable water. When groundwater is extracted from wells, the result is a shift in the natural balance. If the same amount of recharge is applied, then it can be expected that there will be either a reduction in the amount of groundwater held in storage, a reduction in the baseflow to streams, or a reduction in the amount of groundwater that discharges to the ocean. Reductions in the amount of storage result in a lowering of the water table (as evidenced by wells that run dry, and pumps that must be lowered to maintain yield, and the drying up of wetlands). Reductions to baseflow can potentially lead to dry streams, and reductions in the amount of ocean discharge can result in saltwater intrusion (see Section 1.1.2). May of these impacts are manifest not only in the quantity of groundwater that is accessible for consumption, but also in the quality of groundwater that is extracted.

Over the past several years drinking water quality and quantity have suffered in response to ever increasing demands placed on several of the Gulf Island's groundwater resources. Complaints of salty tasting and sulphurous drinking water are becoming more common, especially during summer months when the seasonal population of the island grows and when recharge of the groundwater system is at a minimum. However, since there are many interrelated factors such as climate, topography, ecology, geology, and hydrology that affect groundwater, it is very difficult to pinpoint any definite causes without a well-documented bench mark study.

1.1.2 Salinization of Coastal Aquifers

In coastal areas, where bedrock is in direct contact with seawater, the denser seawater infiltrates the rocks from offshore and forms a saltwater wedge or saltwater aquifer beneath the less dense overlying freshwater aquifer (Figure 3a). In this respect, freshwater exists as a lens "floating" atop the saltwater. The interface between the fresh water and saltwater is typically not sharp, but rather a zone of diffusion with a salinity gradient across it (Richter and Kreitler, 1993).

The position of the natural fresh water-saltwater interface at depth can be thought of as representing a dynamic equilibrium between two groundwater fluxes. Generally, the water table is at high elevation in inland areas and at lower elevation along the coast. As a result, groundwater flows from areas of high elevation to areas of lower elevation. In most natural coastal areas, the seaward-directed flux of water within the freshwater aquifer exceeds landward-directed flux within the saltwater aquifer, and freshwater is able to flow out into the ocean. In shallow confined aquifers, freshwater can travel significant distances out into the ocean before issuing forth as a submarine freshwater spring. In contrast, when the freshwater flux is low, saltwater moves further inland, and consequently, the position of the freshwater-saltwater interface is situated further inland. It is the position of this interface relative to the locations and depths of coastal pumping wells that determines whether the water pumped is saline or fresh.

Depending on the topography of a given area, the amount of water that recharges an aquifer, the flow patterns within the aquifer, and the spatial patterns and amount of groundwater use, the natural freshwater flux may not be sufficient to keep seawater from flowing inland. Therefore, coastal aquifers are potentially at risk of degradation from contamination due to the process of saltwater intrusion. Saltwater intrusion results in a measurable shift in the position of the

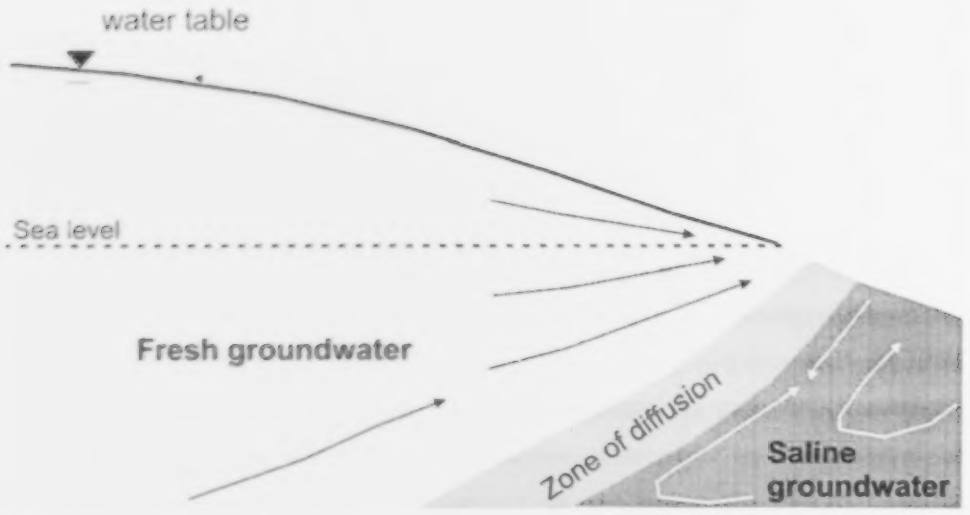


Figure 3a: Circulation of fresh and saline groundwater at a zone of diffusion in a coastal aquifer

Figure 3b: Saltwater intrusion in fractures rock

interface over time and the gradual (or sometimes abrupt) salinization of freshwater resources. Numerous examples of coastal aquifer salinization are known around the world. For example, parts of Florida and the eastern coast of North America are currently experiencing salinization problems. More locally, portions of the American San Juan Islands are contaminated by saltwater.

Contamination of freshwater wells by seawater can occur for a number of reasons. Typically, it occurs as a result of disruptions to equilibrium conditions, which are brought on by development and unsustainable groundwater use. If a well near the shoreline is drilled to a depth that exceeds the depth of the freshwater-saltwater interface or perhaps intersects fractures and rock units that are in direct contact with the ocean, saltwater may contaminate the well even before it is put into use. In areas that historically had good freshwater supplies, saltwater intrusion can be brought on by excessive pumping by one or a combination of wells. Dry summers (and possibly climate change) and the elimination of recharge areas exacerbate the problem of saltwater intrusion, because the reduced freshwater flux is insufficient to compete with the unaffected saltwater flux.

A further layer of complexity that characterizes the Gulf Islands is the presence of fractured sedimentary bedrock aquifers with associated fractures, faults and folds (Figure 3b). Fractures likely serve to further complicate saltwater intrusion processes. Unlike groundwater flow though unconsolidated sediments, flow through fractured bedrock follows discrete flow paths. The path taken by water as it flows though bedrock is defined by the aperture, orientation and interconnectedness of fractures. Fracture zones may provide preferential pathways along which water may flow inland from the ocean under pumping (D. Mackie, personal communication, 2000). Because of their relatively high permeability, fracture zones are also prime targets for drillers in search of potable water. It is this high permeability that can lead to serious problems if coastal aquifers are over developed. Because fracture zones are desirable drilling

targets, several wells may tap the same fracture zone if properties are located in close proximity. The combined pumping of all wells may cause seawater to be drawn into all wells in a given area. Thus, over pumping of coastal wells drilled into fractured bedrock can result in significant landward migration of saltwater into an aquifer. The presence of discrete fractures can also be expected to result in neighbouring wells having completely different hydraulic and chemical characteristics, which may complicate the interpretation of spatial data.

1.1.3 Water Chemistry Data

Water chemistry data obtained by sampling groundwater wells, surface waters and springs can provide important information on groundwater resources. Therefore, a water sampling program is normally a component of most detailed hydrogeological investigations. In addition to providing baseline data that can be used for future studies related to water quality deterioration and resource sustainability, these data may be used to:

1. **Define general trends that describe the natural evolution of water.** In an island aquifer system, groundwater generally evolves from a calcium (Ca) – bicarbonate (HCO_3) composition (recharge areas) to a sodium (Na) – chloride (Cl) composition similar to seawater (discharge areas).

2. **Identify the recharge and discharge areas based on two main criteria:**
    - The amount of total dissolved solids (TDS). As groundwater moves through the ground it dissolves minerals. Generally, the longer the residence time in the subsurface the higher the concentration of total dissolved solids.
    - The relative concentrations of chemical species. Chemical processes in aquifers result in certain relative concentrations of dissolved species that can be used to identify the origin of

dissolved species, and thus, provide information on the travel path of groundwater.

3. **Identify areas that have unusually high concentrations of dissolved metals or anions that may exceed drinking water limits**. This information may be useful for identifying areas where development should be curtailed or where alternative water sources may be required.

4. **Study processes that may be active in the system (e.g., saltwater intrusion)**. In coastal aquifers, contamination by saltwater intrusion is a potential threat. Identifying areas that may be prone to saltwater intrusion may be used to develop guidelines for limited development in these areas.

1.1.4 Previous Studies on the Groundwater Chemistry of Gulf Islands

Comprehensive studies of the hydrochemical characteristics of aquifers on the Gulf Islands are limited. Furthermore, of the studies conducted, most have been focused on limited areas of the more populated southern Islands (e.g., Mayne and Saltspring). In the 1970s, a chemical study groundwaters was conducted on Mayne Island to determine the origin of saline groundwater (Dakin et al, 1983). That study included sampling of a small number of wells and leaching experiments on rock chip samples collected during drilling.

Dakin et al. (1983) proposed four possible origins of saline groundwater based on chemical data for Mayne Island:

1. Soluble salts (such as halite) that are present within the sedimentary strata that now exist in zones of active groundwater flow in the bedrock.
2. Marine water trapped in fractured bedrock strata raised above present sea level by isostatic rebound during post-Pleistocene time.

3. Ocean water intruded into bedrock aquifers under present hydrologic conditions.
4. Formational brines that flow upward from deep (>1000 m) sedimentary zones.

Dakin et al. (1983) concluded that saline groundwater on Mayne Island is of a Na-Cl type, and that salinity is not due to the mixing of deep formational brines. Rather the presence of Na and Cl was thought to be due to the slow diffusion of these ions through the mudstones from which they appear to be derived. Active saline intrusion was viewed as being only a minor contributor to the overall Na and Cl concentrations.

Although there are many similarities between the groundwater systems of Mayne and Saturna Islands, it would be imprudent to assume similar causes of salinity as topographic and geologic conditions do vary between these two islands and other islands in the Gulf Islands chain.

1.2 Purpose

The purpose of this study was to collect and interpret hydrogeological and hydrochemical information for groundwater and surface water in order to evaluate the groundwater resource from the perspective of its quantity, quality and overall movement.

The study also aims to investigate the potential effect of island geometry and geological history on the chemical evolution of groundwaters, and to provide a benchmark for future studies tracking changes in water quality. Furthermore this study attempts to chemically define the mechanisms and delineate groundwater flow paths by examining its evolution from inland recharge zone(s) through to coastal discharge zones, and describing the nature and occurrence of saline waters. The complex geology of the area (structural, sedimentological, and

glacial) in combination with groundwater use patterns is expected to have a significant influence on both the spatial distribution of saline waters and the mechanisms of salinization.

Although this study will not directly ameliorate any present groundwater quality problems on Saturna Island, a valuable consequence of the work will be to inform the island's residents of potential hazards. This report may assist the Islands Trust in formulating a long-term community development plan that incorporates groundwater protection. Furthermore, the work will hopefully serve as a summary of the information regarding groundwater conditions on Saturna Island that may be used for future reference or study.

1.3 Study Objectives

1. To acquire representative samples of groundwater and surface waters for Saturna Island and to assemble a chemical database.
2. To interpret these data in order to:
    a) determine the spatial distribution and the nature of occurrence of various chemical constituents found dissolved in groundwater.
    b) identify local recharge and discharge zones on Saturna Island.
    c) delineate flow regions on the basis of topography and geochemical trends.
    d) explore potential processes that may be controlling natural groundwater evolution, in particular, salinization by saltwater intrusion.

1.4 Scope of Work

The specific tasks undertaken as part of this study included:

1. Collecting groundwater, surface water (fresh and ocean) and rainwater samples from a representative number of appropriately distributed sample locations.

2. Analyzing unprocessed analytical lab and field data using specialized groundwater modeling and plotting software.
3. Summarizing island geometry as it relates to the hydrogeology of Saturna Island.
4. Correlating geology to the occurrence of geochemical anomalies by analyzing the spatial distribution of such anomalies.
5. Summarizing analytical and field geochemical results into a geochemical database.

2.0 REGIONAL SETTING

2.1 Geology

To better understand the groundwater regime on Saturna Island, it is necessary to have some rudimentary knowledge of the geology. The main factor controlling island topography, and hence, the groundwater flow system is bedrock geology. There are both major structural synclinal (down-warping) and anticlinal (up-warping) fold axes trending west-northwest, named the Prevost Syncline and Trincomali anticline, respectively (Fontaine, 1982). These two fold axes control the location of two prominent ridges on the island, Brown Ridge (overlooking Plumber Sound), and the second unnamed ridge running the length of the north side of the island (Figure 4). Brown Ridge has gentle slopes on the down-dip northern side, while the southern side drops off as steep cliffs. The ridge to the north, containing Mt. David and Mt. Elford, does not have a pronounced slope that corresponds to dip. The highest peak on the island is Mt. Warburton Pike at 410 metres. The island coastline is mostly rugged, consisting of wave-cut cliffs and steep promontories as on East Point and Croker Point. Furthermore, many offshore rocks and islets surround the island.

2.1.1 Stratigraphy

The bedrock geology of Saturna Island is composed solely of sedimentary rocks belonging to the Late Cretaceous Nanaimo Group (about 91±3 Ma to 66±2 Ma). The group is generally divided into ten formations, of which primarily the upper four comprise of the bedrock outcrops found on Saturna Island (Figure 4). Although their nomenclatures have varied depending on author, Mustard, (1994) follows with; Geoffrey, Northumberland, de Courcy, and Cedar District. The strata consist mainly of alternating interbeds of sandstone, shale, and some conglomerate. These were deposited under mainly marine conditions by a series of complex overlapping transgressive submarine fan cycles. The conglomerates, sandstones and siltstones are more commonly exposed because the shale tends to weather rapidly.

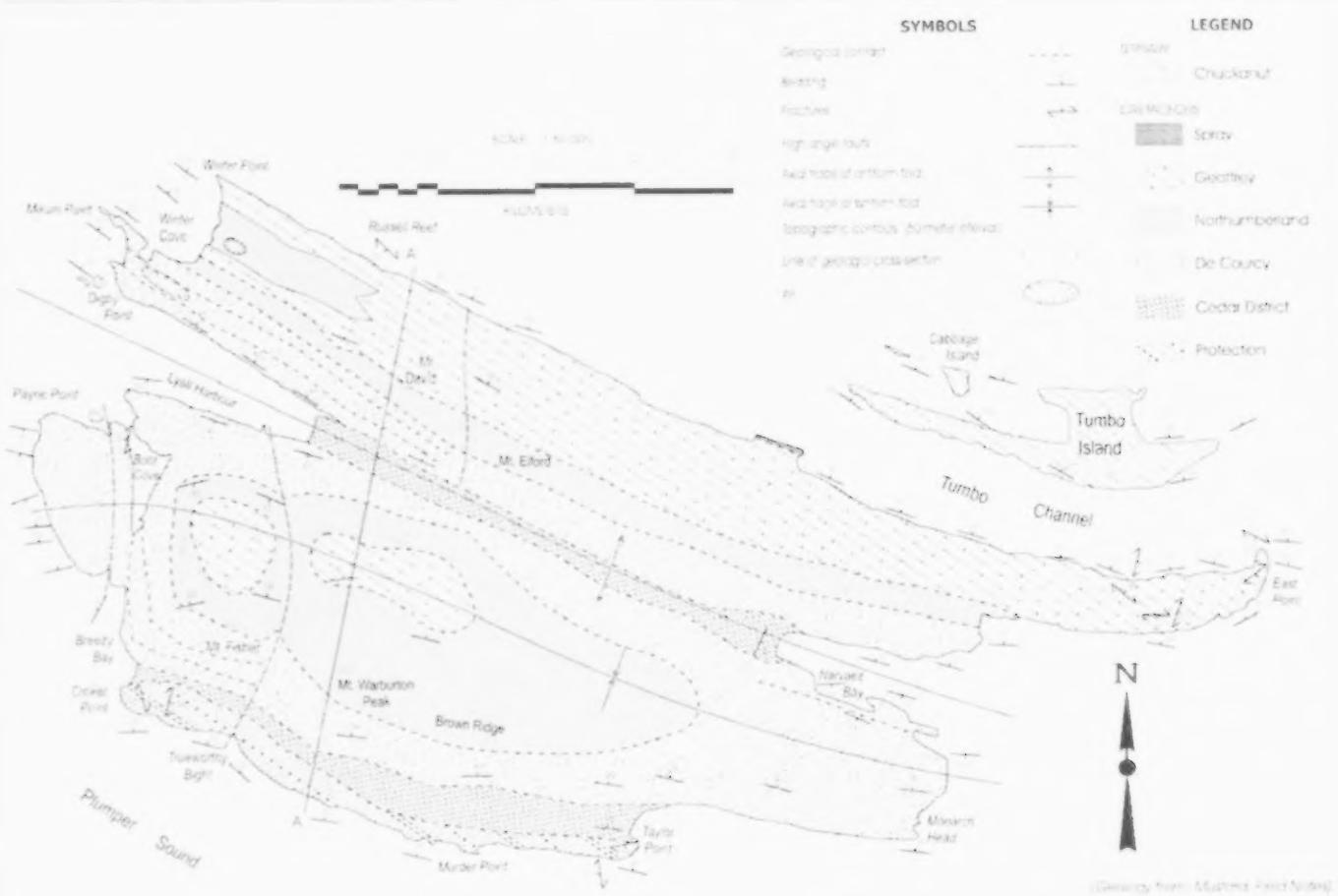


Figure 4: Bedrock Geology of Saturna Island

The area of the old Nanaimo Basin, into which these sediments were deposited, lies along a narrow northwest trending belt in and around the Strait of Georgia. The Nanaimo Group strata can be found on Vancouver Island, the Gulf Islands, and small portions of the San Juan Islands of Washington State (Figure 1). In all, over 3000 metres of Nanaimo Group sediments accumulated during a period of 25 million years. It is estimated that 3000 metres of younger Tertiary sediments had once covered the upper Nanaimo Group. However, erosion has almost completely removed the overlying clastic cover within the Strait of Georgia. Tumbo, Patos, Sucia, and Matia Islands are all that remains of the Tertiary strata outcroppings within the confines of the Strait of Georgia (Mustard and Rouse, 1994). The following lithofacies descriptions, depositional environments, and ages concerning Saturna Island stratigraphy are summarized from Muller and Jeletzky (1970) and Mustard (1994), while information pertaining to the Chuckanut Formation on Tumbo Island comes from Mustard and Rouse (1994).

Protection Formation

Location: Located on the south shore of Saturna Island from Saturna Beach to Taylor Point. **Lithofacies:** Consists primarily of sandstone with interbeds of mudstone near the upper contact. Minor quantities of conglomerate with sub-rounded pebble and cobble sized clasts. The parent material consists of gneiss, granite, quartzite, chert, and volcanics. **Thickness on Saturna:** Only 60 metres are visible above sea level. **Nanaimo Group:** Thickening south-eastward from 30 metres in Comox outcrop area, to > 400 metres on Pender Island. **Depositional Environment:** Shallow marine in northern area, to deep shelf submarine-fan deposition towards the south. Potentially upper submarine-fan for Saturna outcrops. **Age:** Early to Late Campanian.

Cedar District Formation

Location: At the base of southern side Brown Ridge. **Lithofacies:** Generally a coarsening upward formation. The lower sequence begins with silty shale with a

few fine-grained sandstone layers, overlain by fine to medium grained sandstone with sub-angular quartz clasts with some shale interbeds. The upper sequence consists of alternating shale, silty shale, and sandstone. This also forms the gradual transition into the overlying de Courcy sandstone. **Thickness on Saturna:** Thickest sequence is approximately 200 metres. **Nanaimo Group:** About 120 to 200 metres thick in northern areas, to 500 metres in the Southeast. **Depositional Environment:** Moderate to deep marine, generally turbidites as part of the extensive lower and middle facies of submarine-fan complexes. **Age:** Late Campanian.

de Courcy Formation

Location: Constitutes the bulk of the steep southern cliffs of Brown Ridge, Monarch Head, Old Point Farm, and areas slightly above sea level around Lyall Harbour and Narvaez Bay. **Lithofacies:** Mainly brown-grey sandstone. Subrounded, fine to medium grained quartz sand with minor feldspar, mica and carbonaceous material. Base is mostly massive pebbly sandstone. The rock is very resistant to weathering. **Thickness on Saturna:** 300 to 425 metres thick. **Nanaimo Group:** thickening from 200 to 250 metres on Denman, to 450 metres in southern Gulf Islands. **Depositional Environment:** Moderate to deep marine, mostly middle and upper submarine fan facies in major fan complex. **Age:** Late Campanian.

Northumberland Formation

Location: Middle portions of Brown Ridge, Winter Cove area, and a thin strip along the southern side of the northern ridge. **Lithofacies:** Mostly interfingerings of sandstone and shale beds. Beds higher in succession are graded sandstone-siltstone-shale and are 2 to 15 cm thick. This formation was quarried in Winter Cove. **Thickness on Saturna:** 150 to 180 metres thick. **Nanaimo Group:** Generally

200 to 300 metres thick. **Depositional Environment:** Low energy deposition area, "distal" to fan complexes. **Age:** Late Campanian.

Geoffrey Formation

Location: At the top of Brown Ridge, and entire length from East Point to Russell Beach along north side of the Island. **Lithofacies:** Consists of well-sorted sandstone with minor quantities of coarse conglomerate, while shale interbeds are prominent throughout. **Thickness on Saturna:** > 500 m thick. **Nanaimo Group:** Varies from 150 metres to > 500 metres. **Depositional Environment:** Middle and upper submarine fan facies. **Age:** Late Campanian to early Maastrichtian.

Spray Formation

Location: Only present on the small tip of land on north side of the Island near Tumbo Channel, (Gaines' are present property owners). **Lithofacies:** Grey mudstone and siltstone with some sandstone interbeds. **Thickness on Saturna:** Only approximately 50 metres visible. The rest is submerged under Tumbo Channel. **Nanaimo Group:** Varies from 100 to > 300 metres throughout Gulf Islands. **Depositional Environment:** Areas "distal" to and between main channels of submarine fan complexes. **Age:** Early Maastrichtian.

Chuckanut Formation

Location: Tumbo and Cabbage Islands. **Lithofacies:** Overall coarsening upward trend. Non-marine conglomerate, sandstone, and mudstone. On Tumbo Island, sandstone is dominant. **Thickness on Tumbo Island:** Approximately 500 metres thick. **Chuckanut Formation:** Up to 6000 metres thick, but majority has been eroded. **Depositional Environment:** Meandering and braided fluvial setting. **Age:** Upper Paleocene (Tertiary).

2.1.2 Structure

The Nanaimo Group sequence was deformed by compression into a fold and thrust belt during the Laramide orogeny in the middle Eocene (Mustard, 1994; England and Hiscott, 1991). Neogene (33.7 Ma to 1.8 Ma) uplift of the Coast Belt to the east, and tilting of Wrangellia terrane (Mustard, 1994) to the west caused uplift and erosion of the Nanaimo Group so that is it only partially exposed across the region (Figure 1).

The structural features present are related to the major faulting and folding events (Mustard, 1994). On Saturna, the resulting syncline-anticline combination is evident in the present outcrop pattern. Strata dip angles range from almost horizontal atop the anticline to 60° on the north side of the island (Figure 4). There are, in fact, only two significant faults on Saturna Island. The first is Harris Fault, which strikes NNE to SSW, crosses Brown Ridge between Mt. Fisher and Mt. Warburton Pike, and apparently ends at the anticline fold axis. The second has the same strike and separates Mt. David from Mt. Elford (Figure 4). These are both high angle faults with minimal vertical displacement (Mustard, personal communication).

2.1.2 Surficial Geology

Southwestern British Columbia was subjected to four periods of glaciation during the Pleistocene, interrupted by interglacial intervals, where ice melted and vegetation returned. However, little geologic evidence remains from earlier glaciations, as the youngest advances tend to remove older deposits. As with the other islands in the Georgia Basin, Pleistocene and even younger Holocene deposits cover much of Saturna Island. The Pleistocene sediments include moraine and glaciofluvial material (Figure 5). These sediments accumulated during advance and retreat of Fraser Glaciation, the last glacial advance of the

Figure 5: Surficial Geology of Saturna Island

Cordillera Ice Sheet, which reached this area approximately 20,000 years B.P. (Clague, 1986). Other Holocene sediments such as fluvial, organics and colluvium cover bedrock and older glacial sediments. The unconsolidated surficial deposits are generally less than 2 m thick, and surficial material overlying bedrock does not exceed 6 m (Dixon-Warren, 1997). Due to the ongoing process erosion by wind and water, and mass wasting, much of this unconsolidated sedimentary cover has been removed. Furthermore, the sediments tend to be thickest at the bottom of valleys, and are generally only present as thin veneers on the upper portions of hills and ridges.

During the Pleistocene, ice cover depressed the land by as much as 300 m below present day sea level along the Strait of Georgia (Clague, 1983). During the post-glacial period, eustatic sea level rise, along with residual land depression, caused the island to remain submerged (Mathews et al., 1970). Evidence such as relic wave-cut platforms and an exposed glaciomarine diamicton on Saturna confirm interpretations of submergence (Dixon-Warren, 1997). On neighbouring Mayne Island, Dakin et al. (1983) estimated that the island was submerged up to the present 150 metre elevation. Mathews et al. (1970) estimated that ice cover left the area very rapidly 13,000 years B.P., and that by 12,000 years B.P., the land had risen to present day sea level. Since that time the land surface elevation has not changed significantly.

2.1.3 Soil Horizon

Soils derived from sandstone and conglomerate parent rock are typically shallow, coarse textured, and drain well, reflecting the character of the underlying bedrock, which may be well fractured, and therefore allows good penetration of roots and rainwater infiltration. Deeper, dark coloured and loamy textured soils are also present and generally overlie shale parent material. The central valley between Lyall Harbour and Narvaez Bay has a deeper soil horizon. Soils in higher topographic regions are derived mostly from glacial deposits that have

been altered due to movement, and are mapped as colluvium. These soils are also shallow due to the steeper relief, and have a coarse to loamy texture (Eis and Craigdallie, 1980). The surficial geology provided in Figure 5 allows soil types and characteristics to be determined for specific areas on Saturna Island.

2.1.4 Ecology

Saturna Island lies within the Strait of Georgia Coast Forest Region, and in the drier sub-region of the Coastal Douglas Fir zone, reflecting the predominant tree species. However, vegetation type varies throughout the island. On dry, disturbed, and southern facing slopes, species also include Lodgepol Pine, Arbutus and Garry Oak. Whereas on moist northern slopes, species include Red Cedar, Western Hemlock, Grand Fir, Red Alder and Big Leaf Maple. Beneath the tree cover, vegetation is mostly Salal with lesser amounts of Oregon Grape (Eis and Craigdallie, 1980).

2.2 Climate

Saturna Island lies in a region of mid-latitude and upper air westerlies. It experiences low pressure cyclonic and high pressure anticyclonic systems in conjunction with the westerlies. During the summer months, there is an increase in the high-pressure systems, which causes a reduction in precipitation. A "rainshadow effect", created by the Olympic peninsula in the United States to the south and mountains on Vancouver Island, further reduces precipitation. In winter, low-pressure cyclonic or frontal systems are most prevalent, and are responsible for overcast skies and bring the majority of precipitation (Fontaine, 1981).

Average annual precipitation on Saturna was low at 757 mm for the period (1967-1981), compared to Vancouver, which received 1540 mm annually (1951-1980). Temperatures, meanwhile, are mild with an annual average of 10°C (Environment Canada, 1998). This is partly due to the surrounding body of water,

which acts as a climate regulator in both summer and winter. Saturna has the least precipitation of all Canadian Gulf Islands; 75% of the precipitation falls from October to March. The winter surplus (above average precipitation) is 400-800 mm, while in summer the deficit is 50-200 mm. On average, Saturna receives 25 cm of snow annually, which either becomes surface runoff, infiltrated groundwater, or is lost by evaporation (Fontaine, 1982).

Saturna Island and the neighbouring Gulf Islands have some of the characteristics normally found in arid regions. In the summer of 1998, the average temperature was approximately two degrees Celsius above normal. During this period, precipitation was minimal, resulting in very little surface drainage. This condition also caused little or no seepage to occur in discharge zones due to a lowered water table. Also as a consequence of the dry summer, several wells on Saturna Island, in both low-lying shoreline areas and topographically higher areas experienced depressed water tables (that dropped below pump levels in some instances).

2.3 Topography and Recharge

The topography of Saturna Island is largely controlled by the underlying geology. Erosion of mudstone-dominant bedrock is enhanced relative to the more competent sandstone-dominant bedrock. Thus, we see a topographic pattern in the Gulf Islands whereby the less resistant bedrock units erode away to leave valleys. Competent bedrock units typically form the ridges at high elevation.

The topography of the island controls not only the patterns of surface runoff, but also the local hydrology (surface drainage features) and the groundwater flow system. When the terrain increases in ruggedness, overland flow velocities increase, causing a decrease in the amount of infiltrating surface water. This is significant because areas like the steep southern cliffs of Brown Ridge, which are anticipated to be recharge zones for the low lying ground between Croker and

Taylor Points, likely do not permit much infiltration. In contrast, areas like the center of East Point, which represents a significant portion, if not all of the water catchment (recharge zone) for this area, is relatively flat and will, therefore, permit more precipitation to infiltrate prior to runoff (Hodge, 1995).

All water that does not infiltrate moves overland, collects in surface streams and pond, and eventually drains into the ocean. This surface flow is vital to the ecology of many areas. The surface drainage system consists of the larger Lyall Creek (sample LC-3), another creek draining into Narvaez Bay (sample NB-2), and mainly small ephemeral streams, all of which have flows that depend on climatic conditions. There are no naturally formed lakes on Saturna. Money Lake is man made and which provides municipal water to many households in the Lyall Harbour area. Several swamps are situated throughout the island, both at high and low elevation, and some were sampled (e.g. East Point swamp EP-S and Narvaez Bay swamp NB-S).

Water that does infiltrate the subsurface becomes part of the groundwater system. Topographically high terrains are generally considered recharge zones, although recharge is not restricted to areas of high elevation and typically occurs over a large percentage of the island surface. The definition of a recharge area is an area where the net direction of groundwater flow is in a downward direction. The water table in recharge areas, while at considerable depth below ground surface, is at higher elevation than found in valleys. For example, the static water level in a well on Brown Ridge is greater than 100 metres deep. In discharge zones, the net direction of groundwater flow is in an upward direction. Discharge zones are typically within valleys or all along the coast, where the hydraulic head is close to the surface, or in some cases, rises above ground surface. Well EP-9 and EP-11 are flowing artesian wells. Flowing conditions occur because the wells tap into a confined layer in the aquifer that is under a high hydraulic pressure (Figure 6).

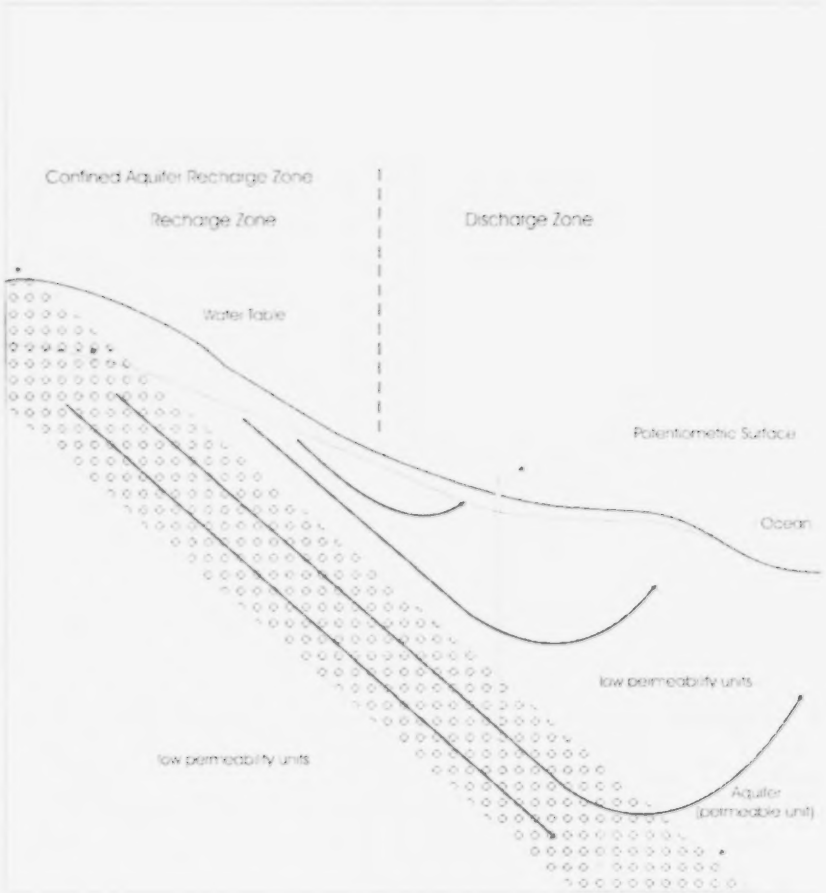


Figure 6. Confined aquifer and potentiometric surface.

Groundcover also plays an important role in the hydrology of the island. During periods of heavy precipitation, ground cover reduces and retards surface runoff. Thus, areas of dense forest floor coverage on northern slopes will have no or minimal surface runoff during short periods of precipitation, since more rain is intercepted by the tree canopy prior to reaching the ground surface, thereby allowing infiltration to occur. On the dry southern slopes, which lack forest floor vegetation, there is greater susceptibility for overland flow to occur during both long and short periods of precipitation. This process decreases the amount of infiltration and promotes evaporation.

The annual fluctuation in groundwater levels is associated with cycling of recharge, which is linked directly to precipitation. The dependence of the groundwater regime on precipitation is evident in the well hydrograph for observation well #290 in the Winter Cove area (Figure 7, BC MELP).

Figure 8 roughly defines the extent of potential recharge areas for Saturna Island. This map indicates that recharge occurs locally on the island and occurs predominantly at higher elevations over a large percentage of the island surface. Further support for the statement that recharge occurs locally is provided by the geochemical results (see Section 4).

On the basis of these potential recharge areas, Suchy (1998) identified 5 major groundwater flow regions for Saturna Island:

1. Tumbo Channel
2. Lyall Harbour
3. Boot Cove
4. Narvaez Bay
5. Spray Point - Tribune Bay

Two sub-regions were also identified because of denser populations:

1. East Point
2. Winter Cove

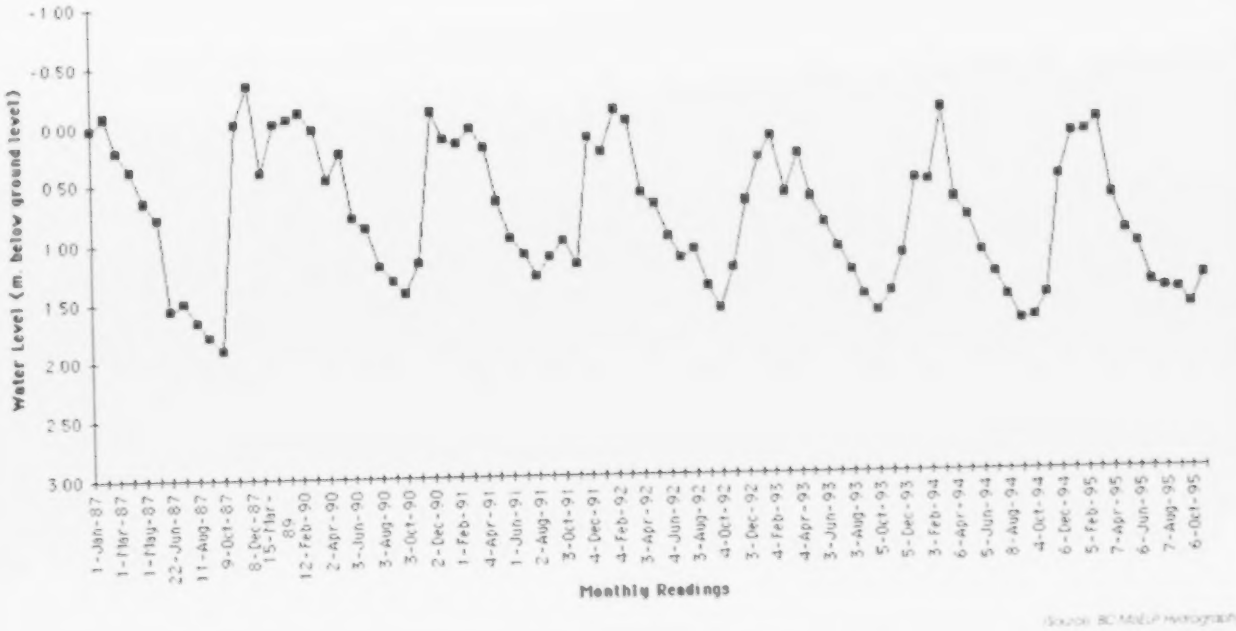


Figure 7: Hydrograph for observation well number 290, Winter Cove: Jan 87 to Oct 95

Figure 8: Potential groundwater recharge zones

Figure 9 illustrates the five flow regions and two sub-regions. The boundaries of the flow regions were identified on the basis of topography and likely groundwater flow paths. These flow regions may not represent true groundwater catchment basins because topographic divides do not strictly address variability in the subsurface geology and structure, such as bedding contacts and fractures that may bypass topographic controls. Nevertheless, they are likely generally representative of groundwater flow regimes. The use of chemical data will provided valuable constraints to the overall interpretation of the groundwater flow regions on Saturna Island.

2.4 Hydrogeology

The groundwater regime is regulated by surface water, which in turn is regulated by a combination of factors including climate, hydrology, ecology and topography. When surface water infiltrates the subsurface, it is further altered and controlled by geologic factors. Furthermore, since ocean water surrounds the fresh water regime, the interaction between the two must also be considered as a significant factor. The interrelation between these factors affects the spatial distribution and characteristics of a groundwater system, yet each serves as an indicator of local conditions.

In general, the nature of the bedrock will have an important bearing on the pattern of groundwater movement and the type of dissolved chemical constituents in groundwater. The lithology (rock type and composition), distribution and thickness of water-bearing units are important factors controlling the flow groundwater. Aquifers are defined geological units that contain and are capable of yielding large quantities of water. In contrast, aquitards are geological units that transmit water at very low rates, and thus, have low yields.

The hydrogeological properties of bedrock (porosity and permeability) are dependent on size and lateral extent of void space and the connection offered by

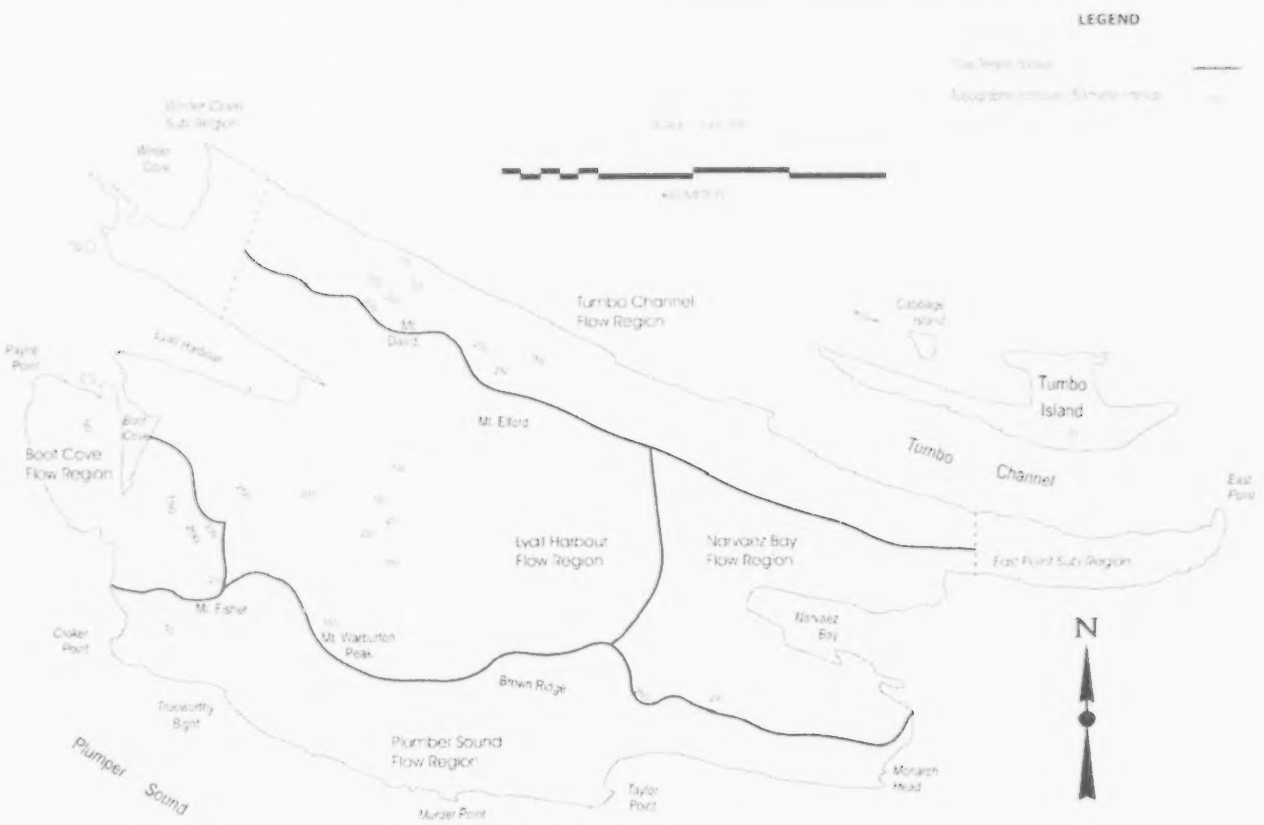


Figure 9. Flow Regions

fractures. For unconsolidated materials, porosity and permeability depend on packing of grains, grain shape and arrangement, and the variation in clast size. Porosity is a measure of the water-bearing capacity, and is an integral part of the rock's capability to hold water. Porosity of a rock depends primarily on the degree of cementation, the state of solution and fracturing. Permeability meanwhile, is the ease with which fluids pass through a porous or fractured media, and is reflected in a property called the hydraulic conductivity, K.

Darcy's Law (Eq. 2.1):

$$q = \frac{Q}{A} = -K\frac{\Delta h}{\Delta \ell} = -\left(k\frac{\rho g}{\mu}\right)\frac{\Delta h}{\Delta \ell} \qquad \text{(Eq.2.1)}$$

quantifies the rate at which a fluid discharges (Q) through an area A. This flux q, is proportional to the hydraulic gradient ($\Delta h/\Delta \ell$). k represents permeability, ρ is fluid density, μ is fluid viscosity, and g is gravity. Table 1 provides the ranges values for hydraulic conductivity, porosity and permeability for the types of rocks found on Saturna Island (Freeze and Cherry, 1979).

Table 1. Ranges of hydraulic conductivity, porosity and permeability for unfractured rocks types, and unconsolidated clean sand for comparison.

Rock type	Hydraulic Conductivity	Porosity	Permeability
	m/s	%	cm^2
Sandstone	10^{-10} to 10^{-6}	5 to 30	10^{-13} to 10^{-9}
Shale	10^{-13} to 10^{-9}	0-10	10^{-16} to 10^{-12}
Clean Sand	10^{-6} to 10^{-2}	25-50	10^{-9} to 10^{-5}

The hydrogeological properties of the Nanaimo Group rocks generally fall at the low end of the ranges shown in Table 1. In general, primary porosity (i.e., that

resulting from the porous grain network) is extremely low. Porosity is <5% as measured by industry in association with oil and gas exploration, and is related to extensive cementation and diagentic infilling by zeolites. The low porosities have resulted in coarse-grained bedrock units that have a much-reduced capacity to transmit water (i.e., a very low permeability). As such, water can be expected to flow primarily through the fractures, the mudstone units or along bedding contacts, which offer secondary porosity and permeability. Thus, while it is commonly held that mudstone units are aquitards or aquicludes, and that coarser-grained units (e.g., sandstones and conglomerates) are aquifers, these classifications are not necessarily representative of the Nanaimo Group rocks.

Because the primary porosity and permeability of the rocks is so low, the amount of water available for use depends on whether the fractures are present, their size, their abundance, and whether they are free of clay or other fine-grained sediments or secondary mineralization. Because lithology can potentially exert control on how fractures propagate through the rock column, contrasting mechanical properties between alternating sandstone, conglomerate and silt-mudstone units (or interbeds) may result in the concentration and/or increased intensity of fracturing within the finer grained units (D. Mackie, personal communication 2000). In areas that host poorly fractured bedrock or where no major fractures are intersected by a well, the groundwater yield will be low, as permeability is much reduced.

On Saturna Island, fracture intensity appears to be an essential factor controlling the availability of groundwater. This is consistent with observations by water well drillers on most islands who record higher yields, in fracture zones, within mudstone units, and at bedding contacts. In addition, dominant fracture sets and fault zones may also provide the permeability necessary to support high yielding wells. A research study by Mackie (M.Sc. in preparation) is aimed at investigating groundwater and permeability relationships in fractured rocks on the island.

The implication is that rock type and structure will have a significant bearing on groundwater flow. In complex geological systems, such as the Gulf Islands, where the rock type alternates between sandstone and mudstone and where the rocks have been subjected to different stresses associated with tectonic deformation, the groundwater flow patterns can be expected to be complex and difficult to characterize. At best, and without detailed studies on the hydrogeology, it is only possible to describe the overall geological attributes of the system, infer the general movement of groundwater, and characterize the chemical composition of groundwater based on large-scale trends.

A theoretical representative hydrogeologic cross-section depicting the groundwater flow on Saturna Island was developed (Figure 10). The line of cross-section is shown in Figure 4. The movement of groundwater in the subsurface will necessarily be much more complicated than is shown because of variations in rock type and geological structure (i.e., fracturing). Nevertheless, the diagram serves to illustrate the concept of local recharge and the dynamics of the groundwater flow system.

2.3 Groundwater Usage

In 1985 a water well record was determined for the Gulf Islands (Hodge, 1985).

Gabriola Island	1237
Saltspring Island	1176
Pender Island	517
Galiano Island	495
Hornby Island	406
Mayne Island	341
Denman Island	224
Saturna Island	**100**

Of the 100 wells on Saturna Island, most were located in the areas of Lyall Harbour, Boot Cove and East Point peninsula. At the time of this study (summer 1998), the approximate number of wells was 150 in use, 50 not yet in production and approximately 50 abandoned. Lyall Harbour has approximately 30

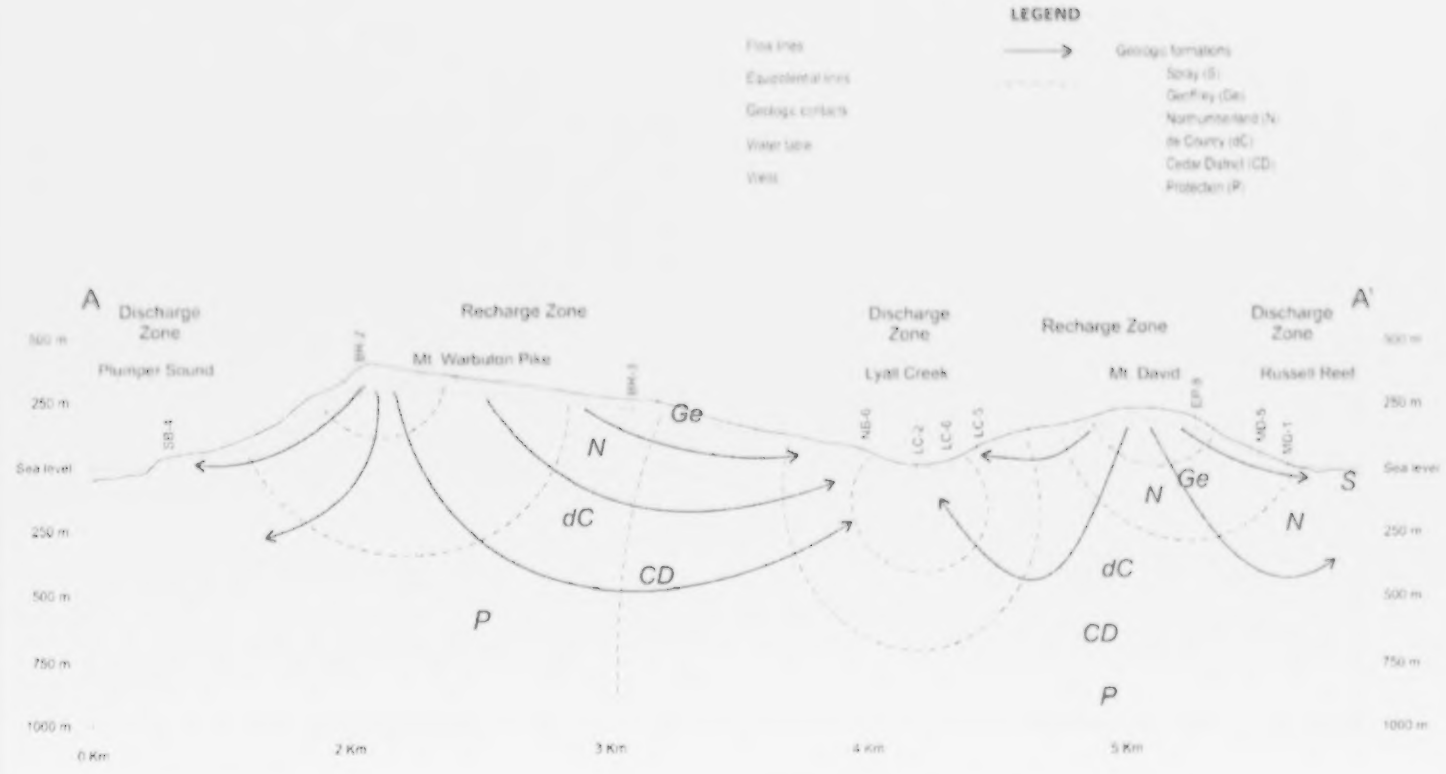


Figure 10: Hydrogeological cross-section

abandoned wells; most of which are shallow (< 15 metres). In 1985, the Boot Cove area had only 8 wells, most of which were abandoned due to high salinity and because the area, along with Lyall Harbour, became serviced by municipal water from Money Lake. On East Point peninsula, at least 5 wells have been abandoned due to high salinization. Approximately 30 wells were drilled in the Winter Cove area in the early 1980's, however most are not yet in production. Presently, 20 wells are in production in the Winter Cove Sub-Region. Continuing development is evident by the 13 wells that were installed in August 1998 near Russell Reef on the north side of the island. Much of Saturna Island remains undeveloped.

Residential and recreational property development on the Gulf Islands has historically been most intense along coastal exposures, and development on Saturna Island is no exception to this general trend. Because of this, groundwater resources are potentially at risk for degradation due to contamination by seawater and reduced yields due to close spacing of wells along the coast.

3.0 GEOCHEMISTRY

3.1 Methodology

3.1.1 Data Collection

A total of 107 water samples were collected during two field sampling programs in the summers of 1997 (23 samples) and 1998 (84 samples). These samples were collected from a number of sources, which included private and community wells, surface waters (lake, swamp and streams), rainwater, and the ocean. The locations of all samples are shown in Figure 11. Some samples were collected at different time during pumping tests on a few wells to check for water quality variation during groundwater extraction.

Samples that were submitted to CanTest Ltd. for dissolved metal and anion analysis were collected in 500 ml and 1 litre, high-density polyethylene (HDPE) bottles, respectively. Sample collection and preservation protocols for this project are generally in accordance with the guidelines outlined in ASTM Standards on Environment Sampling (1994). Anion samples were not filtered nor preserved, and were kept cool (at approximately 10°C) in environmental coolers. All metals samples were filtered using 45μm filter papers. Only half of those samples collected for metal analysis in June 1998 were preserved with nitric acid to a pH of 2 because of field technical problems. The remaining samples were kept cool and later acidified at the laboratory. There appears to be no discrepancy in the results between the sample groups preserved in the two different ways.

Isotope samples were collected at several sites, in both 1997 and 1998. These were sent to the University of Waterloo in Waterloo, Ontario, for analysis. In 1997, seven samples were tested for ^{18}O, Deuterium, and Tritium, whereas the 31 samples from 1998 were only tested for ^{18}O and Deuterium. These data have been retained for future study and are not provided in this report.

Figure 11: Sample location map

Sampling of surface waters employed grab sampling. Groundwaters from drilled wells were largely sampled from outside household taps or, in some instances, from taps located at the well. All sampling from residential and community wells was done with the express consent of the well owner, or in the owner's absence, from someone managing the property. Due to the inherent variability in the plumbing setup at each well, it was generally not possible to collect a sample before the water had passed through the pressure tank, but the water was allowed to flow for several minutes to ensure that the pump had cycled a few times. In a couple of cases, water was sampled directly from cistern holding system. Nevertheless, sample integrity does not appear to have been degraded. When necessary, samples were collected after filtration systems.

Field measurements of pH, temperature and total alkalinity were taken immediately upon collection of the sample. pH and temperature were measured using a Hanna HI 9023 temperature-compensated pH meter, and total alkalinity was measured on a filtered sample using a Hanna HI 4811 field alkalinity test kit. Alkalinity was also measured by the analytical lab. Total dissolved solids (TDS) was measured using a Hanna® 10/1990 handheld meter. Field measurement of these three parameters is necessary so as to record, as close as possible, the "in situ" chemical character of the water. Changes in temperature and the presence of atmospheric gases such as O_2 can result in significant changes in pH and total alkalinity values due to disruptions in the chemical equilibrium. Off gassing of some samples was observed (e.g., MD-2), but gas composition and partial pressures were not obtained. It is not known if H_2S or CO_2 or possibly some other gas (methane?) was released. Other field parameters measured include conductivity and dissolved nitrate. Detection limits for all equipment used are reported in Appendix A.

Three control samples were collected for this study. CS-1 is a sample of distilled water, which was used as a field blank by running the water through all field tests and filtering equipment. Field blanks are used to verify laboratory analyses as

distilled water should not contain any dissolved ions. Sample CS-2, is ocean water taken from Saturna Beach in July 1997. It was collected to provide an end-member composition for interpretation of water chemistry evolution. The third sample (CS-3) is a rainwater sample, which was collected from a precipitation holding tank from a dwelling along the south shore of East Point.

3.1.2 Data Analysis

All samples were sent to CanTest Ltd. for analysis. Dissolved metals were measured using an ICP-MS (Induced Coupled Plasma-Mass Spectrometer), while pH, total hardness, and anions were analyzed according to procedures outlined in ASTM Standards on Environmental Sampling (1994) and the British Columbia Environmental Laboratory Manual. Detection limits are reported along with the chemical analysis results in Appendix A. The samples tested in 1997 were analyzed with lower detection limits and are so identified.

Unprocessed chemical data were entered into a database and chemical results sent to individual homeowners on Saturna Island. Unprocessed data were entered into Solmineq® (Alberta Research Council, 1988). Solmineq is a solution and chemical equilibrium software program that can be used to calculate chemical speciation (including the carbonate speciation, which is of primary importance to this work), charge balance errors, the saturation indices for various minerals, and the re-adjustment of the solution equilibrium to field conditions. Specifically, the solution is adjusted to provide the speciation and mineral equilibria at the measured field pH and temperature conditions rather than the lab conditions. Bicarbonate concentrations (HCO_3^-) are used later for plotting and interpretive purposes. These data were then entered into AquaChem® (Waterloo Hydrogeologic Inc., 1997) and Microsoft Excel (7.0) for the plotting of Piper diagrams, bivariate graphs, and bicarbonate – pH graphs.

To construct a Piper plot, the relative concentrations of three cations and three anions (expressed in milliequivalents) are calculated. Typically, Ca, Mg and Na are the cations, and HCO_3, Cl and SO_4 are the anions, although other combinations may be useful for different types of studies. For each sample, the cation composition is plotted on the right triangle and anion composition on the left, and the sample points are projected onto the diamond. Bivariate plots (or scatter plots) show the relative concentrations of two constituents for different samples. These plots are useful for visualizing trend in the data, and for illustrating key groundwater evolutionary processes.

3.1.3 Charge Balance Error

When a laboratory analyses water samples, a calculation known as a charge balance error is normally performed. The magnitude of the charge balance error can be determined using the following relation (Freeze and Cherry, 1979):

$$E = \frac{\sum zm_c - \sum zm_a}{\sum zm_c + \sum zm_a} \times 100 \qquad \text{(Eq. 3.1)}$$

where E represents the charge balance error, and z and m represent the ionic charge and molality (defined as moles/kg), respectively, of each ionic analyte. The charge balance error is one method used to assess the integrity of a sample's analysis because all solutions should be electrically neutral. For an analysis to be considered "very good" it should fall in the range of ±5%. About half of the samples in this study have CBEs greater than ±5% (Table 2). High CBEs may indicate a problem with the lab analysis, or that one or more ion was not analyzed. It must be noted that determining the magnitude of CBE is dependent on capturing the charge contributions of each ion. The absence of a given ion will result in an increase or decrease in CBE depending on the concentration of the missing ion and on its associated ionic charge. If an ion with a high concentration and ionic charge is not included in the analysis then the associated CBE will be large. On the other hand, if an ion with a low concentration and low ionic charge

Table 2. Analyzed and calculated charge balance errors.

Sample ID	TDS	Analyzed	Calculated	Sample ID	TDS	Analyzed	Calculated
CS-1*	1	-100	-90.5	LC-1	240	-5.73	-5.98
NB-2*	140	-34.03	-34.54	WC-13	370	-5.67	-6.02
EP-09*	160	-22.27	-22.45	MD-2	>1990	-5.39	-5.42
OPF-2*	70	-20.44	-20.67	WC-05	310	-5.30	-5.48
MD-3**	190	-18.96	-19.55	EP-11	90	-4.8	-4.84
NB-5**	220	-17.68	-18.07	EP-13	100	-4.796	-4.814
EP-22**	170	-17.5	-17.62	EP-27C***	>1990	-4.74	-4.88
EP-14**	80	-16.66	-16.76	EP-27D***	>1990	-4.66	-4.80
EP-17**	460	-16.55	-16.71	BB-S	40	-4.58	-4.03
BR-1**	10	-16.48	-16.7	EP-27B***		-4.065	-4.19
NB-6**	260	-15.62	-15.77	EP-29A***	600	-3.66	-3.68
EP-08	220	-14.37	-14.49	MD-5	220	-3.13	-3.17
EP-23	210	-14.34	-14.48	EP-29B***	510	-2.74	-2.74
EP-18	530	-14.26	-14.33	EP-27A***		-2.72	-2.85
SB-3	300	-14.19	-13.57	LC-8	470	-2.29	-2.34
BB-4	60	-13.69	-13.94	SB-HP	590	-2.19	-2.22
EP-19	250	-13.62	-13.83	SB-6	140	-1.79	-1.76
NB-4	150	-13.07	-13.28	WC-02	270	-1.67	-1.70
WC-11	350	-13.01	-13.21	LC-4	480	-1.51	-1.57
WC-09	290	-12.89	-13.32	WC-07	650	-1.38	-1.41
WC-08	340	-12.76	-13.18	EP-07	280	-1.303	-1.322
EP-01	350	-12.54	-12.69	SB-7	140	-0.91	-0.92
BB-2	80	-12.52	-12.69	WC-06	530	-0.83	-0.85
EP-12	180	-12.45	-12.6	EP-31	120	-0.42	-0.43
EP-24	200	-12.12	-12.25	WC-15	270	-0.10	-0.09
BB-1	120	-11.83	-12.06	EP-32	280	0.12	0.15
MD-4	200	-11.83	-12.12	SB-1	500	0.29	0.29
EP-05	450	-11.55	-11.63	EP-06	>1990	0.4196	0.426
EP-04	440	-11.3	-11.5	SB-5	140	0.94	0.96
EP-16	230	-11.16	-11.27	SB-2	570	1.11	1.13
WC-04	480	-11.04	-11.42	LC-2	1270	1.13	1.20
EP-15	190	-10.7	-11.09	EP-26A***	210	1.52	1.552
WC-P	60	-10.65	-11.31	MD-1	210	1.94	2.00
WC-HP	1660	-9.99	-10.98	EP-S	200	2.13	2.47
BB-3	170	-9.78	-9.98	NB-3	>1990	2.91	2.95
EP-21	440	-9.75	-9.84	EP-26B***	230	3.003	3.065
NB-S	40	-9.56	-9.60	WC-14	350	3.05	3.11
OPF-P	60	-8.98	-9.05	EP-03	480	3.18	3.23
WC-01	180	-8.94	-9.13	BR-2	170	4	4.02
WC-03	530	-8.90	-9.75	EP-29C***	1190	4.15	4.29
SB-4	250	-8.87	-9.25	EP-20	670	4.4	4.5
WC-12	280	-8.53	-8.78	EP-02	550	4.57	4.64
CS-2	>1990	-8.26	-8.73	NB-7	120	4.62	4.77
CS-3	60	-8.14	-7.84	NB-8	170	4.90	5.03
BB-5	250	-7.35	-7.42	LC-5	220	5.00	5.13
WC-S	510	-7.01	-6.96	LC-6	140	6.02	6.15
EP-10	200	-6.83	-6.94	EP-30	150	6.06	6.21
BR-S	50	-6.66	-6.65	OPF-1	70	6.36	6.47
NB-1	290	-6.61	-6.71	LC-3	70	6.65	6.91
EP-28A***	970	-6.00	-6.07	ML-2	90	9.45	10.70
WC-10	310	-6.00	-6.22	ML-1	80	13.92	14.22
LC-7	250	-5.93	-5.97	EP-25*	240	24.4	24.82
EP-28B***	870	-5.92	-5.97	MD-S*	50	34.06	36.89
				WC-BP*	400	62.81	63.49

Negative values signify that the total anion equivalents are larger that the cation equivalents.

* Samples discarded due to extremely large charge balance errors.

** Samples will be used for analysis, but will be deemed suspect if they plot as outliers.

*** Multiple samples from same well collected at different depths or during pumping at different times.

is missed in the analysis, then the associated impact on CBE will be small. As such, it is very important to capture the dominant ionic species in a sample. Another consideration is that for samples with low concentrations of dissolved species, the effect of a small error in concentration is amplified.

Analyzed values in Table 2 represent the raw output from laboratory tests (total concentrations of a particular dissolved species). *Calculated* values represent those mass balance errors that are calculated by Solmineq, and represent the sum of errors for calculated ion species. The resulting analytical errors ranged from 0.10% to 62.81% (Table 2). Typically, an analysis is considered acceptable if the charge balance error is <15%. Only 41 of the 107 samples have charge balance errors < 5 %. 66 samples are <15 %, and 7 are above 20%.

Several explanations for the calculated discrepancies were explored. For those samples that were not preserved with nitric acid in the field, metals might settle out of solution prior to testing. If this hypothesis is true, then un-preserved samples should produce negative charge balance errors (an excess of anions). However, this is not the case as the samples in question have even distribution between negative and positive errors. Another explanation for the shortcoming between cations and anions might be that some elements were not tested for. This is also an unlikely explanation because a full metal scan was undertaken and all major anions were analyzed. A third explanation is that equilibrium chemical conditions were not present in the aquifer. This implies that there is a thermodynamically unstable subsurface environment or possibly a tendency toward disequilibrium brought about by sampling. A fourth explanation is poor analytical procedures by the lab.

The integrity of the data collected for this study was determined by comparing both the calculated and lab CBE. The distinction between suspect and unacceptable CBE was based on CBE ranges. Most labs take a CBE of <±5% to be acceptable (Freeze and Cherry, 1979). CBE values in the range ±10% to

±20% were considered to be suspect, while values in excess of ±20% were deemed unusable for the purposes of this study. Samples identified with "*" in Table 2 have been discarded due to unacceptably high charge balance errors (higher than 20%). Discarded samples include five groundwater samples, one surface water sample, and the distilled water control sample (CS-1). Samples labelled "**" in Table 2 represent water analyses that also have high errors (15 to 20 %), but that will be used for further analysis unless the sample points fall as outliers when graphed. Suspect samples include six groundwater samples. At some sampling locations multiple water samples were collected, and these are identified with "***". These samples were either obtained from different depths within the well or at different times during a pumping test. Of the 107 samples collected, only 100 samples remain for investigation. All conclusions presented in this report assume accurate results for the remaining samples.

The following is a summary of the methodology and analytical lab results obtained during this study. Four groups will be discussed, and the chemical characteristics summarize the results found in Appendix A:

1. Control Samples
2. Surface Water
3. Spring Water
4. Groundwater

3.1 Control Samples

Control samples CS-1, CS-2 and CS-3 represent the field-blank, ocean water and rainwater samples, respectively. CS-1, the distilled water sample, contained essentially no dissolved ions. All dissolved metals were below detection, the pH was 5.47, and total alkalinity and conductivity are 3.3 mg/L (as $CaCO_3$) and 3.3 μS/cm, respectively. There does not appear to have been any contamination of the sampling equipment by improper flushing and cleaning.

Samples CS-3 and CS-2 were sampled to represent end-member compositions for geochemical evolution analysis. The rainwater sample, CS-3, represents the "ideal" starting composition for infiltration water, while CS-2 represents ocean water (chemically evolved). Being end-member compositions the respective chemistries are markedly different.

As it did not rain during any of the field sampling trips, CS-3, was collected from a cistern on East Point, and therefore, is not likely representative of the rainwater composition over much of the island. The conductivity was 208 μS/cm, while the pH was 5.84. The dissolved metals, sodium (Na), potassium (K), calcium (Ca), and magnesium (Mg) were all low at concentrations of 10 mg/L, 1.65 mg/L, 4.29 mg/L, and 1.8 mg/L, respectively. The anions, chloride (Cl), sulphate (SO_4^{2-}), and bicarbonate (HCO_3^-) were 25.8 mg/L, 5.4 mg/L and 11.6 mg/L, respectively. The weather station situated at high elevation and remote from the coast on Saturna Island reports average concentrations for rainwater of 1.21 mg/l Cl^-, 0.68 mg/l SO_4^{2-} and 0.67 mg/l Na^+ (CAPM81414A, Saturna). Sample contamination during collection and the naturally elevated TDS levels common in coastal precipitation, due to sea spray all contribute to variations in the chemical composition of a rainwater sample. As well, geographic location for rainwater collection can affect its chemical composition. The composition of rainwater collected by Dakin et al. (1983) (HCO_3^- was 0.2 mg/L and pH was 5.65) was used for comparison in most chemistry figures.

C-2 (seawater sample) has a very high conductivity (32800 μS/cm), and as expected, extremely high concentrations of dissolved ions. Cl is the dominant anion at 18400 mg/L, followed by Na at 8530 mg/L and SO_4^{2-} at 2150 mg/L. Ca and Mg were also high at 385 mg/L and 996 mg/L, respectively.

3.2 Surface Waters

Surface water samples consist of Lyall Creek (LC-3), Money Lake (ML-2) and six swamp specimens (WC-P, WC-S, NB-S, BR-S, EP-S and OPF-P). In most surface water samples, HCO_3^- is the major anion and Cl^- is the second most abundant, while Ca^{2+} and Na^+ are the major cations.

Lyall Creek receives surface runoff and possibly groundwater discharge along a valley in the Lyall Harbour flow region (Figure 9). Money Lake is man-made and receives primarily surface runoff. Most swamps are situated at high elevation and likely represent the composition of precipitation and local shallow groundwater. The electrical conductivities (EC) for these swamp waters are all below 166 μS/cm, HCO_3^- values are all below 52.5 mg/L, and pH falls between 6.5 and 7.5. Pond-water sample WC-P, although appearing similar to other surface water samples (Figure 12), has a high EC (994 μS/cm) and resembles the composition of groundwater from the Winter Cove area (see Figure 16). Its chemical character suggests that this pond may originate as a groundwater seep. The chemical composition of sample EP-S is also distinct from the other swamp samples, and plots close to the composition of other East Point groundwaters (see Figure 15). Its high EC (324 μS/cm) suggests that this swamp also may be a groundwater seep associated with discharge. Alternatively, the swamp may be a local recharge area for waters on East Point, but it may be more saline due to ocean spray.

3.3 Spring Waters

Of the eight spring water samples, six have a chemical composition similar to the surface waters and all tend to plot in a cluster on the Piper plot (Figure 12). These samples have EC values between 141 and 460 μS/cm, and a range of pH between 6.2 and 6.8. HCO_3^- is the dominant anion in all spring samples. In half the samples, Cl^- is the second dominant anion, while in the other half, SO_4^{2-} is the second dominant anion. The major cations are Ca^{2+} and Na^+. Dissolved SiO_2

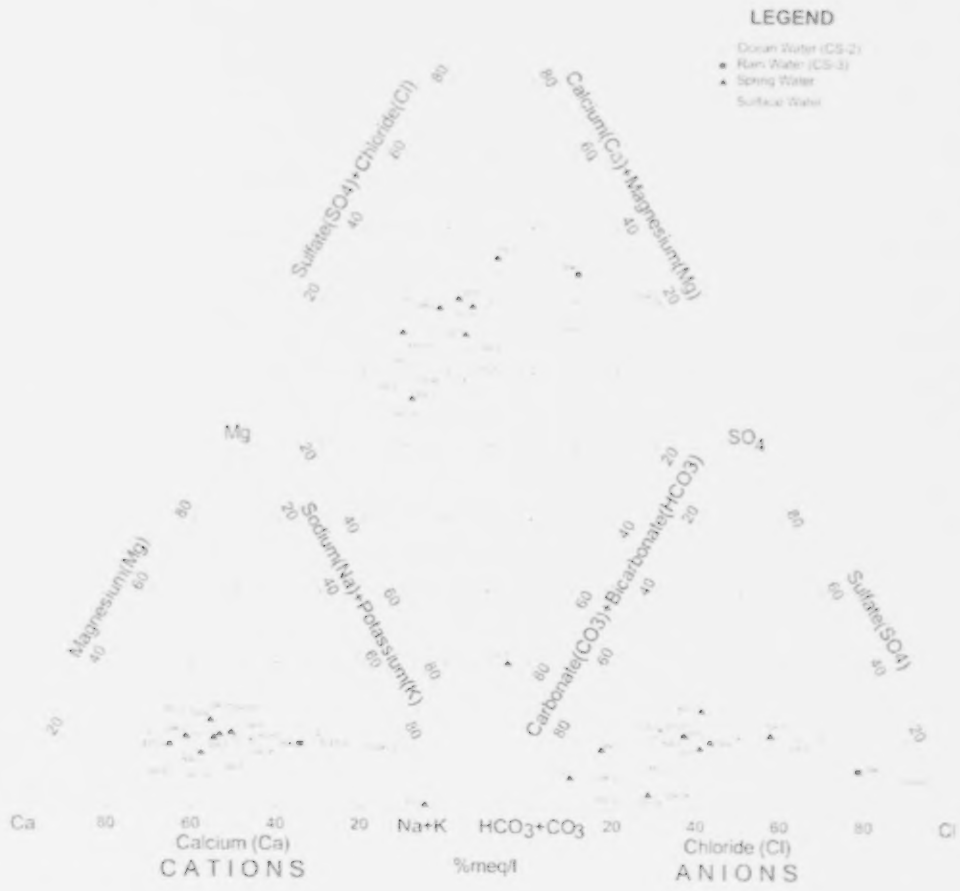


Figure 12: Piper diagram for surface and spring water samples.

is typically less than 10 mg/l.

The low EC of most spring waters and low (Na)/(Ca+Mg) molar ratios suggest that the springs have a chemically immature composition compared to most groundwaters (see groundwater discussion below). Figure 13a illustrates this point by showing the trend of chemical evolution. In addition, most springs have a Cl/HCO_3^- molar ratio less than one (Figure 13b), suggesting a shallow source, or certainly, no contact with deep saline waters. LC-7 has an exceptionally Na/(Ca+Mg) molar ratio (Figure 13a), suggesting that this water has lost Na, perhaps by cation shift. However, the low Cl/HCO_3^- molar ratio suggests that cation shift may be accompanied by mineral dissolution (perhaps calcite, dolomite or feldspar) producing HCO_3^-.

3.4 Groundwater

The composition of groundwater on Saturna Island is variable. Three distinct compositions can be identified using the Piper plot (Figure 14):

1) chemically immature groundwaters, which plot near the center of the Piper plot,
2) chemically more evolved groundwaters, which plot directly below the immature waters near the bottom edge of the Piper diamond, and
3) highly evolved groundwaters, which plot near ocean water.

A number of samples have an intermediate composition, and plot between these type waters. In addition to their different plotting positions on the Piper plot, which reflects the composition of the sample, these samples have significant differences in measured field parameters and total concentrations of dissolved species. The processes by which groundwaters evolve, which are reflected in the compositions of intermediate groundwaters, are described under General Groundwater Evolution (see Section 4.0).

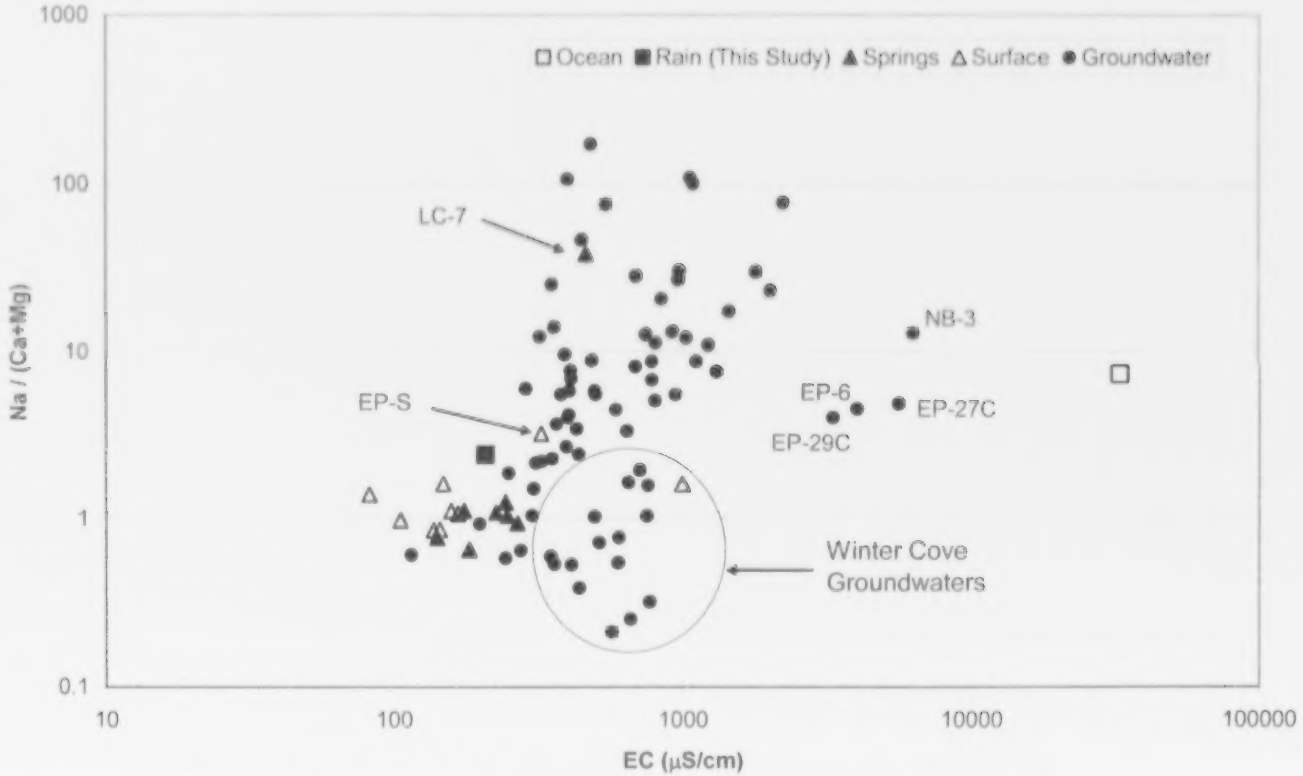


Figure 13a: Na/(Ca+Mg) versus electrical conductivity (EC)

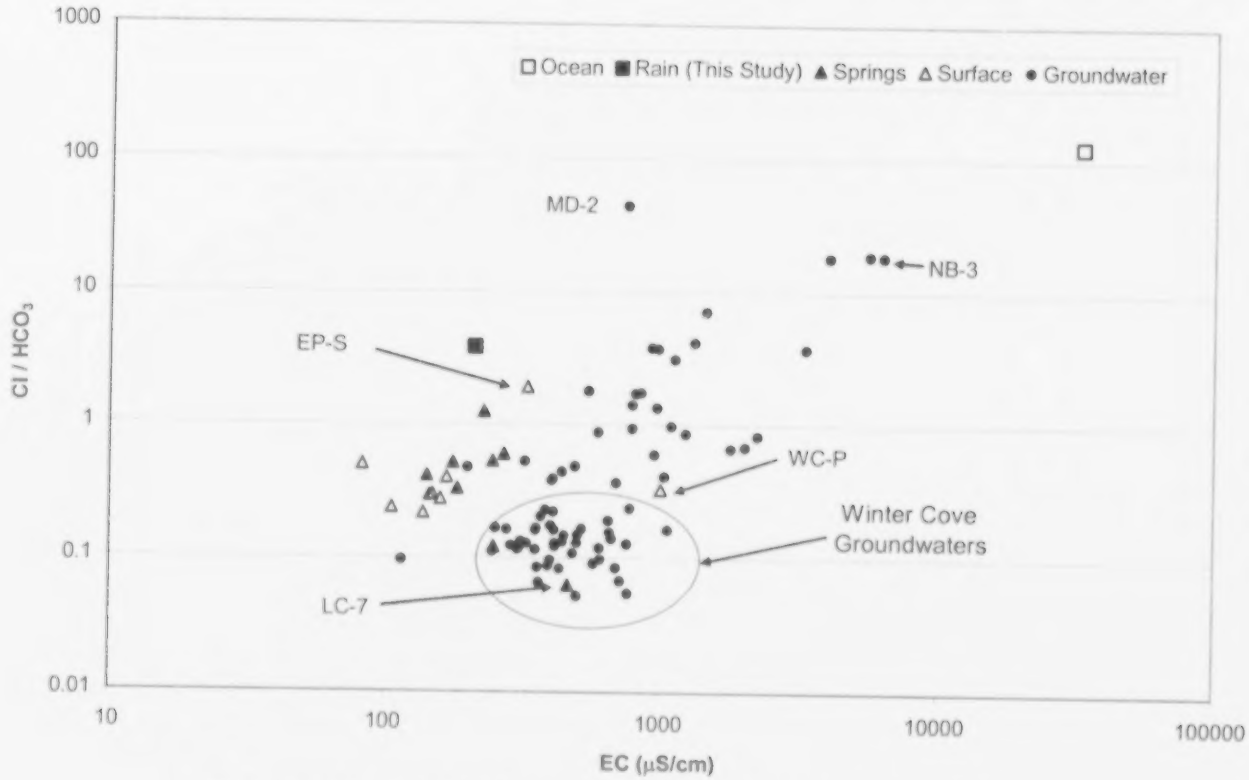


Figure 13b: Cl/HCO3 versus electrical conductivity (EC)

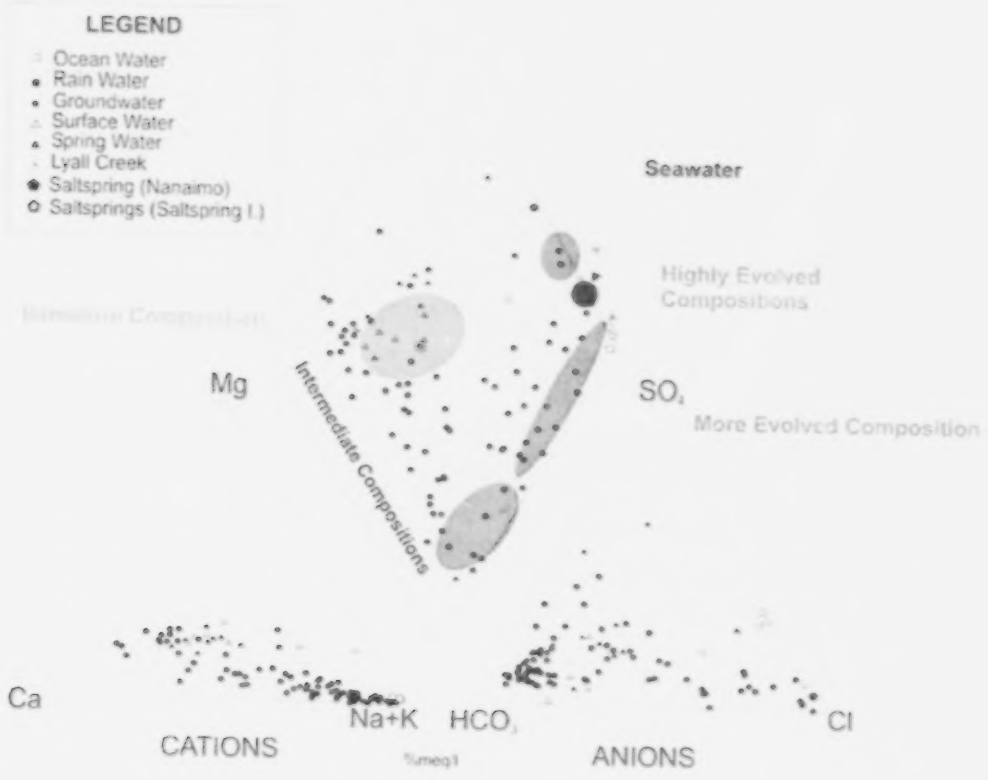


Figure 14: Piper diagram of all sample chemical data illustrating immature, intermediate, more evolved and highly evolved groundwater compositions

Groundwater samples with the highest total dissolved solids (TDS) values (>1,990 mg/L, maximum for apparatus used), correspond to those with the highest conductivity values (at least 3,900 μS/cm) because conductivity is an alternative measure of TDS. Low TDS values are typically due to shorter flow paths, absence of contamination and/or a shorter duration of water-rock interaction on the surface.

Total alkalinity was measured both in the field (Falk) and in the lab (Talk) (Appendix A). Typically alkalinity measurements made in the laboratory are slightly lower compared to field measurements (Richter and Kreitler, 1993). Saturna Island data follow this trend as well; 62% of the laboratory alkalinity values were lower than the alkalinities measured in the field. Approximately 75% of the lab and field alkalinity values were within 15% of each other. HCO_3^-, which was calculated using Solmineq and generally accounts for most of the total alkalinity in groundwater, ranges from a low of 39.9 mg/L to a high of 363 mg/L. The majority of the samples have values between 100 and 300 mg/L, depending on the flow region. Moreover, the values within each flow-region or sub-region are generally of similar magnitude.

Cl is the most variable anion, ranging from 8.3 mg/L to 2,800 mg/L. Cl is the dominant anion and Na is the dominant cation in samples where TDS concentrations are very high. However, samples with moderate TDS levels have HCO_3^- as the dominant anion, especially in the Winter Cove region. Of the fifteen samples in which TDS is lower, Ca is the dominant cation and HCO_3^- is the dominant anion.

SO_4^{2-} concentrations of groundwater samples vary from 1.5 to 671 mg/L, however, only eight samples have concentrations above 124 mg/L; only one exceeded 265 mg/L. A large proportion of samples have SO_4^{2-} concentrations between 15 and 40 mg/L.

The sample groups SB, BR and BB, and EP, corresponding to the Plumper Sound and East Point flow regions, will be used as a representative group for the purpose of summarizing the general chemistry of immature and evolved groundwaters (Figure 15). Figure 15 also includes the sample collected from Lyall Creek (LC-3) and several spring and surface waters collected in these flow regions for comparison. The Piper plots for all sample regions are provided in Appendix B. Chemical anomalies, involving elevated levels of dissolved species such as manganese (Mn), boron (B), fluoride (F) and sulphate (SO_4^{2-}), are summarized separately (Section 3.5).

3.4.1 Chemically Immature Groundwater Compositions

In the Plumper Sound and East Point flow regions, four water samples plot as immature (i.e., near the center of the diamond in Figure 15). These include one surface water sample (BR-S), two springs (SB-5 and SB-6), and one groundwater sample (SB-4). The surface water sample was collected from a swamp near the top of Brown Ridge. The two spring samples were collected from the base of Mt. Warburton Peak, and the groundwater sample was collected during a pumping test at a well on Saturna Beach. Spring and surface waters were discussed earlier, and therefore, will not be discussed further. Therefore, the only groundwater sample in these two flow regions to plot as a young groundwater is SB-4. This sample has a pH 7.57 and an electrical conductivity (EC) of 515μS/cm, consistent with a slightly evolved groundwater. Total alkalinity (226.7 mg/L) is elevated compared to surface and spring waters (under 100 mg/L), and major ion concentrations are generally slightly elevated compared to those measured in surface water samples. This is not unexpected as it is assumed that groundwaters have been resident in the subsurface for a longer period of time, and therefore, have had sufficient time to acquire dissolved constituents.

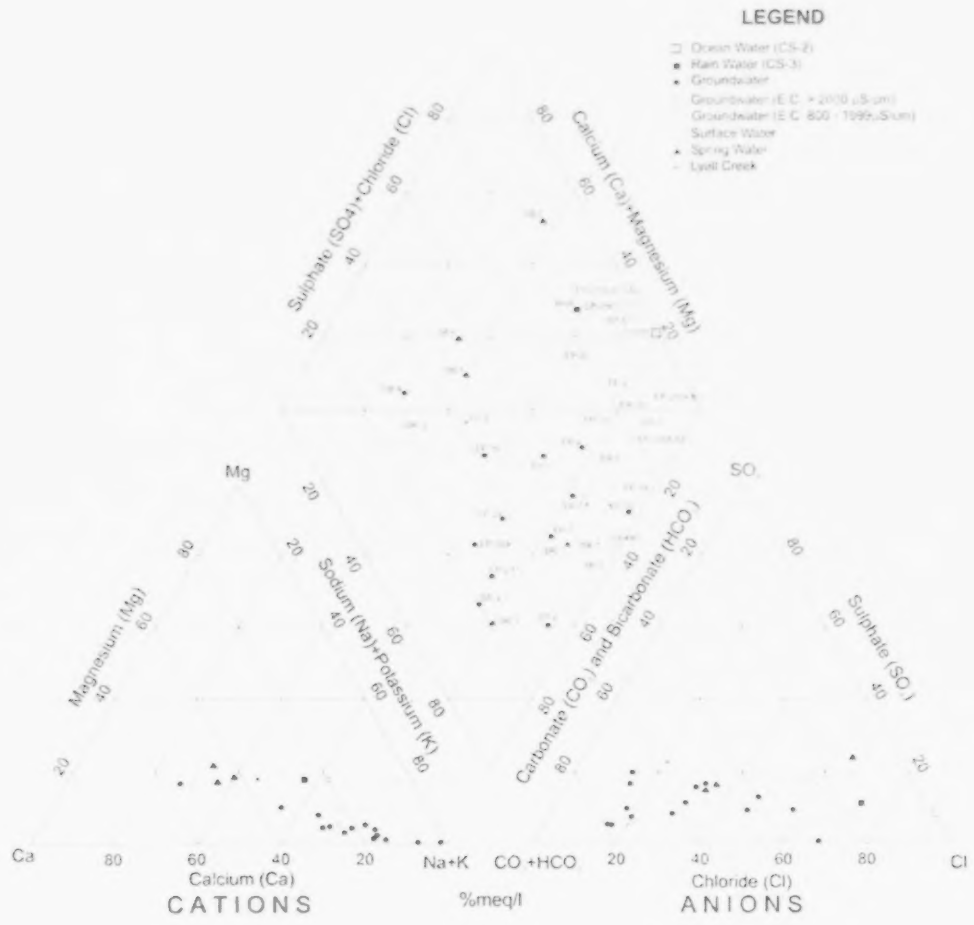


Figure 15: Piper diagram of East Point and Plumper Sound Flow Region samples

SB-4 has a very different composition compared to adjacent wells along Saturna Beach (e.g., SB-1, SB-2 and SB-3), which tend to have a more evolved and often highly evolved composition (see next two sub-sections). The reason for this inconsistency may be related to the fact that the well from which the SB-4 water sample was collected is situated near the Harris Fault (refer to Figure 4 for sample location and position of Harris Fault). The Harris Fault likely acts to circulate water fairly rapidly and bring fresh recharge water from high elevation rapidly down to the coast. In this respect, the short residence time will likely permit only a moderate amount of dissolution, and the high permeability of the fault material will offer ideal conditions for significant flushing by fresh waters.

3.4.2 Chemically More Evolved Groundwater Compositions

Samples EP-19, EP-24, EP-26A, EP-23, SB-3, BB-5 and BR-2 appear to represent more highly evolved groundwaters (listed in increasing order of evolution). The depths of the wells in the Plumper Sound area, corresponding to BB-5 and BR-2, are 244 m and 198 m, respectively. The depth of SB-5 is unknown. The EP wells are all generally less than about 100 m.

The samples plot on a line extending down from the position of the immature groundwaters on the Piper diamond (Figure 15). The Plumper Sound samples appear to be more evolved than the East Point samples, and this is reflected in the chemistry of the samples. With the exception of EP-19 (pH=7.07), these samples are characterized by relatively high pH (7.70-9.04). EC ranges from 351-499 μS/cm, which tends to be higher than that measured in immature waters. Major ion concentrations are relatively consistent, but there is a clear trend of higher concentrations of dissolved species in the Plumper Sound samples compared to the East Point samples. For example, in the EP samples Na varies from 45-62.5 mg/L, while in the Plumper Sound samples, Na varies from 71.6-89.9 mg/L. Ca is low in all samples and ranges from 4.84-25 mg/L, and Mg varies from 0.78-4.06 mg/L. Total alkalinity is lower in the EP samples and

ranges from 150-169 mg/L, while in the Plumper Sound samples it ranges from 141-232 mg/L. Cl is low in all samples and ranges from 14.1-46.2 mg/L.

3.4.3 Chemically Evolved and Saline Groundwater Compositions

The bulk of the samples in the Plumper Sound and East Point flow regions show a tendency to be very evolved, and several are considered saline. Five samples have EC values below 800 μS/cm, but exhibit a more evolved composition than those described in the previous section. These include BR-1, EP-7, EP-17, EP-1 and EP-4. Many of these groundwaters have EC values higher than 800 μS/cm, and are shown as open circles on Figure 15. These include SB-1, SB-2, SB-HP, EP-18, EP-5, EP-21, EP-29(A,B), EP-3, EP-20, EP-2 and EP-28(A,B). EP-29(A,B) were collected at different depths in an abandoned well, and EP-28(A,B) were collected during a pumping test at different times (A was collected earlier than B). The samples with EC values above 2000 μS/cm, and which are considered saline are shown with solid grey circles on Figure 15, and include EP-27(A,B,C,D), EP-29C and EP-6. The EP-27 samples were also collected at different times during a pumping test, and EP-29C is the deepest sample in the abandoned well.

These evolved and saline groundwater samples tend to have high pH values (6.89-9.7) with an average of 8.08. EC ranges from 319-5590 μS/cm, and total alkalinity ranges from 76.2-193 mg/L. The high EC values correspond with higher concentrations of dissolved ions including primarily Na, which ranges from 45-974 mg/L and Cl, which ranges from 23.7-1960 mg/L. Ca is low in those samples that plot below seawater on the Piper plot (8.2-57.5 mg/L) but increases significantly in those samples that plot above seawater (169-297 mg/L).

Most of the samples that are considered to be evolved plot below seawater (seawater is shown as an open square in Figure 15). But, the saline waters (grey circles) plot above seawater. This difference in chemical composition reflects the

pathway of origin for the different waters. Those samples that plot along a line from the more evolved waters discussed in the previous section to seawater, represent an evolution of a Na-rich composition toward a more Cl-rich composition. In contrast, those samples that plot above seawater have a Ca-rich and Cl-rich composition.

3.5 Anomalous Concentrations

In order to examine the occurrence of anomalous concentrations of dissolved species, it is necessary to define acceptable limits. For the purposes of this study, the Canadian Drinking Water Guidelines are used for comparison. While incomplete in many respects, these guidelines offer the only means for assessing water quality. Table 3 shows the Canadian Drinking Water Guidelines and the United States Drinking Water Guidelines. Several constituents have no reported limit. It is important to note that most chemical constituents considered in this study were analyzed at detection limits that are lower than those reported in the drinking water guidelines. For example, the minimum detection limit (MDL) for F (Appendix A) was 0.05 mg/L for most samples and the guideline indicates that concentrations less than 1.5 mg/L are acceptable. However, for both arsenic (As) and lead (Pb), the minimum detection limit (MDL) is above the drinking water limits in a few of the samples, so it is impossible to determine if the measured concentrations meet the drinking water guidelines. Consideration should therefore be given to the MDLs when evaluating anomalous concentrations of dissolved species.

Dissolved manganese and fluoride were found to exceed the limits specified in the Canadian Drinking Water Guidelines in about one third of the wells on Hornby Island (Allen and Matsuo, 2001). The current limits for Mn, and F are set at $\leq$0.05 mg/L and 1.5 mg/L, respectively. The following describe the occurrence of these dissolved constituents on Saturna Island.

Dissolved Mn ranges from 0.001 to 0.97 mg/L and averages 0.091 mg/L. In total, 35 samples exceed the aesthetic limit of 0.05 mg/L for Mn specified in the Canadian Drinking Water Guidelines. High concentrations of dissolved manganese are found in four areas on Saturna Island. The highest concentrations were measured in surface water samples collected from Money Lake (ML-1 and ML-2 with concentrations of 0.93 and 0.47 mg/L, respectively). Money Lake is located north of Mt. Fisher and Mt. Warburton in the center of the island, and provides drinking water to many residents on Saturna. Other areas with high concentrations include East Point peninsula located at the northeastern tip of the island, Winter Cove at the northwestern tip of the island, and Lyall Harbour at the northwest end of the center of the island. Saturna Beach at the southern side of the island, also has elevated manganese levels. Samples from these areas are all groundwater.

- Fluoride (F) concentrations range from <0.05 to 4.3 mg/L with an average concentration of 0.41 mg/L. Five samples recorded F concentrations below the detection limit of 0.05 mg/L, and F was not measured in 12 samples. F exceeds the 1.5 mg/L Drinking Water Guideline in 4 samples that were obtained from wells situated in four different flow regions. Sample MD-5 has a F concentration that only slightly exceeds the Drinking Water Limits, while NB-3, EP-32, and LC-8 have concentrations of 3.5, 4.1 and 4.3 mg/L.

Table 3. Recommended drinking water guidelines for inorganic compounds. (Source: Environment Canada and U.S. Environmental Protection Agency). Concentrations in mg/L.

Constituents	Canada		USA
Alkalinity	30-500		-
Hardness	<120		-
pH	6.5-8.3 units		-
TDS	<1000		
Fluoride	1.5		4.0
Chloride	<=250.0		-
Nitrate	45.0		10.0
Nitrite	3.2		1.0
Sulphate	<=500.0		-
Aluminium		(10)	0.05 – 0.2
Antimony		(10)	0.006
Arsenic	0.025	(8)	0.05
Barium	1.0		2
Beryllium		(10)	0.004
Boron	5.0	(8)	-
Cadmium	0.005		0.005
Calcium		(13)	-
Chromium	0.05		-
Cobalt		(10)	-
Copper	<=1.0		1.3
Iron	<=0.3		-
Lead	0.01		0.015
Manganese	<=0.05		-
Nickel		(10)	0.1
Selenium	0.01		0.05
Silver		(13)	-
Sodium	<=200		-
Thallium	-		0.002
Uranium	0.1	(10)	-
Zinc	<=5.0		-

Footnotes

8. Interm water guidelines
10. Guidelines under review for addition to, or possible changes to, the current value.
13. Parameters identified as not requiring numerical value.

In addition to Mn and F, chloride (Cl) was found to exceed Drinking Water Guideline of 250 mg/L in 9 wells. Sodium (Na) was found to exceed the limit of 200 mg/L in 18 wells. Iron (Fe) was found to exceed the aesthetic limit of 0.3 mg/L in 13 wells.

Hydrogen sulphide (H_2S) gas was detectable in a few well waters, and during sampling, these samples had an obvious rotten egg smell, characteristic of the presence of H_2S. It is important to note however that even small amounts of H_2S can be smelled, and that this gas is generally not harmful at low concentrations. In comparison to Hornby Island, the number of wells with notable H_2S is significantly less.

In order to determine the nature and occurrence of the various dissolved constituents and to attempt to relate these to the geology and hydrogeology of an area, it is sometimes possible to contour the concentrations of each constituent and show them on a map. In order to contour the chemical data, the UTM coordinates for each sample location, as well as the concentration of the constituent of interest, were estimated and input into Surfer (Golden Software, version 7.0). This software package employs an interpolation algorithm to determine the concentration at points that are at intermediate positions between the known values and generates concentration contours from the results. Sample distribution is an important consideration in attempting to interpolate data, therefore, the results of this type of visual analysis should be viewed with caution. As well, the contours extend beyond the island imprint by virtue of the rectangular grid that is employed for contouring.

Contour maps showing the spatial distribution of each of chloride (Cl), fluoride (F), manganese (Mn) and sodium (Na) are shown in Appendix C.

4.0 DISCUSSION

4.1 Major Geochemical Processes

There are three major natural processes, in addition to chemical reactions (such as oxidation-reduction reactions) that commonly contribute to the observed chemistry of groundwaters. These processes may act alone, but are more commonly observed to work in concert with one another:

1. Dissolution of Minerals
2. Cation-Exchange
3. Simple Mixing

4.1.1 Dissolution of Minerals: with Consideration of the Carbonate System

The chemical weathering of rock by water results in the liberation of numerous dissolved ion species (e.g., Na^+, Ca^{2+}, SiO_2, and SO_4^{2-}...). It is by this process that relatively juvenile surface water compositions gradually become enriched in total dissolved solids. The rate and degree to which enrichment occurs are dependent on a number of factors including, 1) the solubility of the minerals present, 2) the temperature and pH of the water, 3) the amount of surface area available for the water to react with minerals comprising the aquifer (fractured rock in the case of the Gulf Islands), and 4) the amount of time that the water is in contact with the minerals (i.e., the residence time).

Carbonate equilibria exercise a dominant control on the evolution of groundwater. Carbonate equilibria pertain to the complex interplay between CO_2 (gas), carbonic acid (H_2CO_3), bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) in aqueous solution. These species are related to each other by the following equation:

$$CO_2(g) + H_2O(l) = H_2CO_3\,(aq) = HCO_3^-\,(aq) + H^+ = CO_3^{2-} + H^+ \qquad (4.1)$$

Subtle shifts in the concentration of CO_2 (g) can result in significant perturbations in the amount of HCO_3^- and CO_3^{2-} present in a groundwater.

The availability of CO_2 (i.e., as measured by the partial pressure of CO_2 (P_{CO2})) dictates whether or not a groundwater evolves under open or closed conditions. P_{CO2} for the atmosphere is $10^{-3.5}$ Bar, while P_{CO2} is slightly higher in the soil horizon due to the production of CO_2 (gas), and is generally about $10^{-1.5}$ Bar. Common sources of CO_2 in the shallow subsurface include the metabolic gases of soil bacteria, root respiration, and atmospheric gases trapped between soil particles.

Open system evolution of groundwater involves a constant source of CO_2 during dissolution of mineral species, while closed system evolution involves the eventual isolation of a groundwater from a source of CO_2. Open system conditions result in a moderate increase in HCO_3^- with an accompanying increase in pH. At the pHs commonly encountered in groundwater (pH=6.5-9.1), HCO_3^- is the dominant carbonate species present. The lack of a CC_2 source, as is the case with closed system conditions, means that the carbonate equilibrium is shifted to the left in equation (4.1) in order to replace H_2CO_3 that is consumed by mineral dissolution reactions (especially calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$). When H_2CO_3 is consumed, there can be a significant increase in pH.

The dissolution of carbonate minerals is generally considered to be a primary source of Ca^{2+}, HCO_3^-, and possibly Mg, in groundwater. This composition is reflected on a Piper Plot. For example, in the Winter Cove sub-region, represented by samples WC, several samples plot in the center of the diamond (Figure 16). These samples include WC-1, WC-2, WC-5, WC-12, and WC-15. The water is Ca-HCO_3 type, reflecting simply the dissolution of carbonate minerals, which corresponds with an immature groundwater composition.

In the absence of other minerals, the concentrations of Ca, Mg and HCO_3^- will increase until the groundwater becomes saturated with respect to calcite and

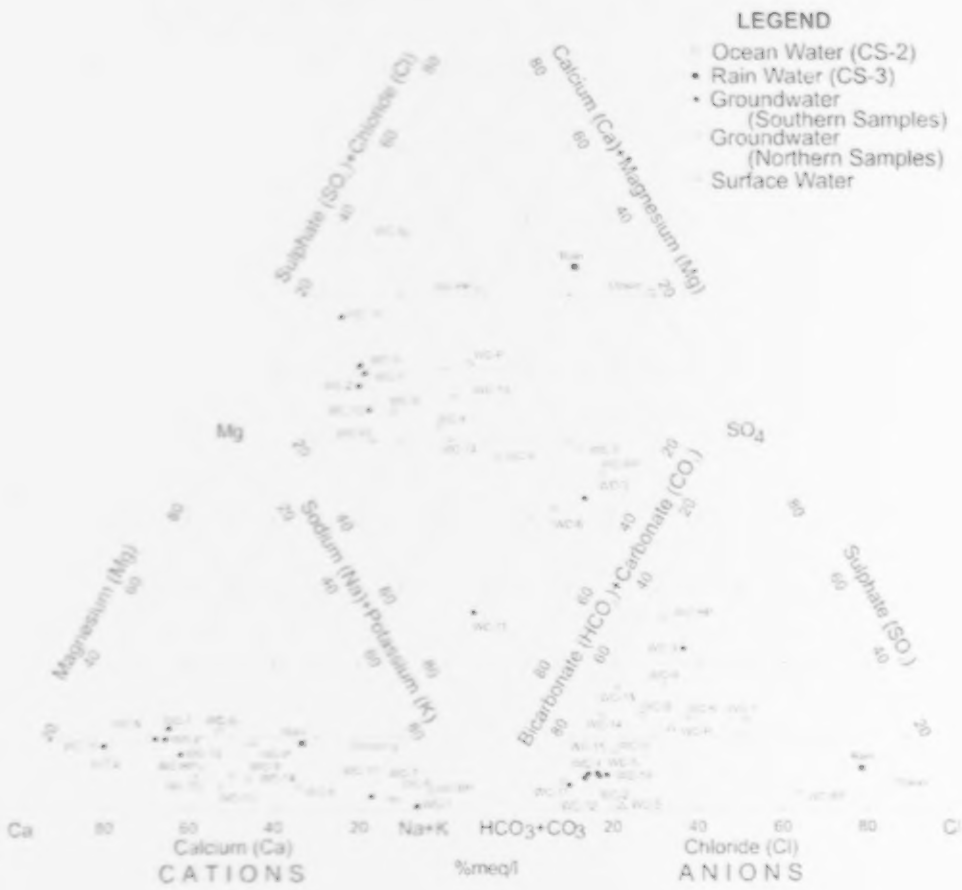


Figure 16: Piper diagram of Winter Cove Flow Region samples

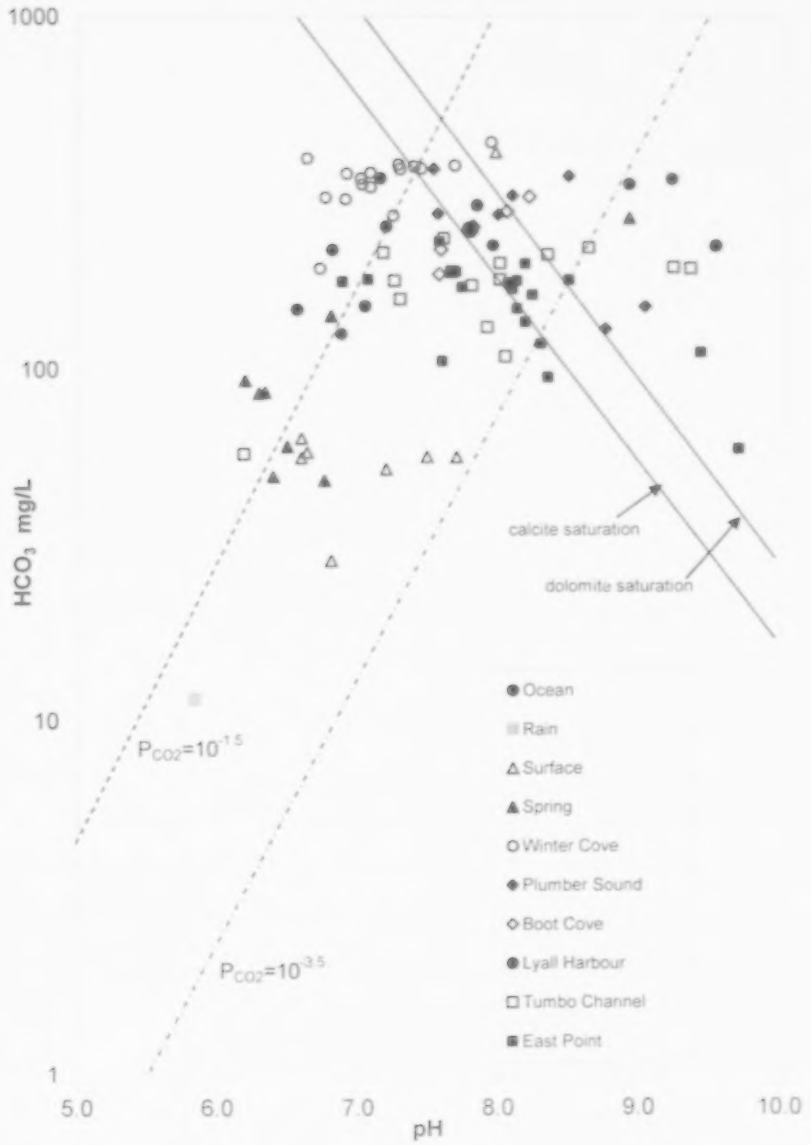
dolomite is achieved and dissolution ceases. The low concentrations of Mg in water samples collected on Saturna Island, probably indicate that the dissolution of dolomite is of minor importance (Allen and Suchy, in press).

Figure 17 is a graph of HCO_3^- versus pH for all samples differentiated on the basis of their sample area. The position of the saturation lines for calcite and dolomite were determined at 25°C for water that is initially ion-free (free of other constituents). If other ions are present in the water, then these lines shift to the right. This implies that in a groundwater with other constituents present, such as in a water that has mixed with seawater and contains higher TDS, more calcite and/or dolomite could be dissolved before saturation is attained. Most groundwater samples plot near or above the calcite and dolomite saturation lines, suggesting that these minerals are close to saturation in the groundwaters. This is supported by the saturation indices calculated for the various carbonate minerals using Solmineq (SI values not reported here).

4.1.2 Cation Exchange

Cation exchange is a process that occurs commonly on clays and other minerals that harbour a negative charge on their surfaces. Cation exchange can be responsible for significant increases in the levels of dissolved Na and simultaneous decreases in the levels of dissolved Ca and Mg. Immature groundwaters in sedimentary aquifers are commonly characterized as Ca-HCO_3 in composition. However, if a suitable exchange media is present in the subsurface (e.g., mudstone interbeds and stringers within otherwise coarse-grained materials) there can be a significant increase in the amount of Na present, due to cation exchange. The degree to which the exchange of Ca (and Mg) with Na occurs is dependent on the pH, temperature, surface area available for exchange, the cation exchange capacity (CEC) of the exchange media (e.g., CEC varies for different clay minerals mudstone), residence time, and the concentration of the solutions involved. Elevated pHs (i.e., lower H^+

Figure 17: HCO3 vs. pH with samples differentiated on the basis of flow region



concentrations), large surface areas and long residence times favour the cation-exchange process (Stumm and Morgan, 1996). Based on these criteria, it would be expected that chemically mature waters that have evolved for extended periods of time would tend to show the strongest signs of cation exchange. From a geologic point of view, increased reaction surface area could be accommodated by groundwater flow through pervasively fractured shale units.

The Tumbo Channel flow region, represented by some EP samples and the MD samples, is selected to illustrate the cation exchange process (Figure 18). This group of samples shows a distinctive trend (indicated by the arrow) whereby Na is enriched in the water and Ca is relatively depleted.

The identification of cation exchange as a major process is also supported by the relationship between pH, HCO_3^- concentration and the cation molar ratio (CMR). CMR is the ratio between sum of (Na) and (K) and the sum of (Ca) and (Mg) (where brackets indicate molar concentrations). For the purpose of this study, the concentration of K is quite low (Refer to Appendix A) and will be ignored in the calculation of the CMR. The CMR offers a method to differentiate between samples that have undergone various degrees of cation exchange. Table 4 lists the CMR ranges that were used to differentiate samples within the various flow regions on Saturna. The variation of HCO_3 as a function of pH and CMR is illustrated in Figure 19.

Table 4. Generalized CMR ratios used to separate samples in Figure 19

CMR Range	Inferred Meaning
CMR>1	Cation exchange not active
1<CMR<3	Cation exchange
3<CMR<20	May indicate additional sources of Na^+
CMR>20	Significant additional sources of Na^+

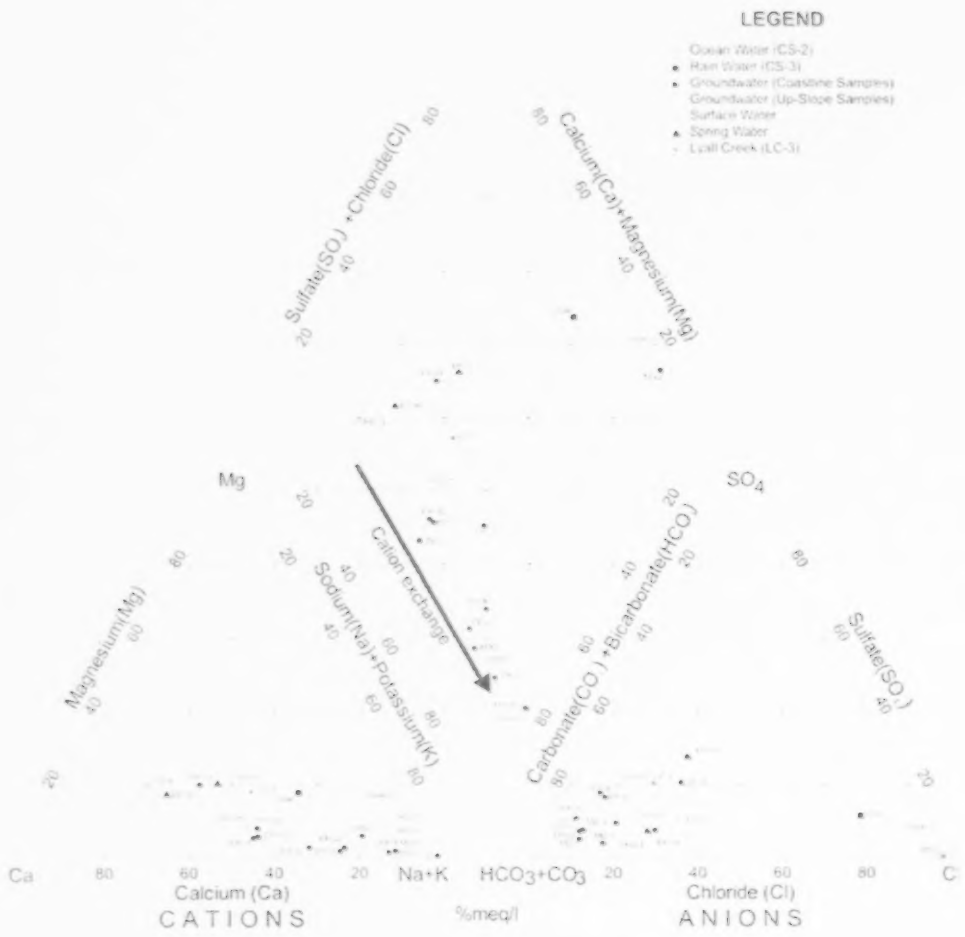


Figure 18: Piper diagram for Tumbo Channel Flow Region samples.

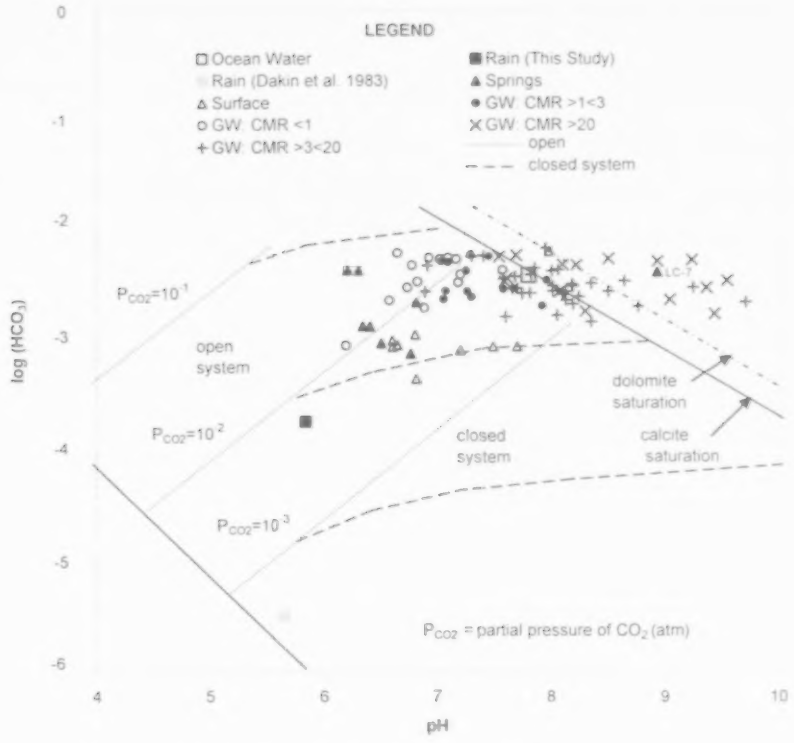


Figure 19: HCO3 vs. pH with samples differentiated on the basis of CMR

Cation exchange is suggested by CMR values above 1. Within the range of 1 to 3, the gain of Na can be expected to be balanced approximately by the loss of Ca in the water. In other words, as quickly as calcite is dissolved, it is lost by cation exchange. At CMR values between 3 and 20, more Na is accumulating than can be explained by dissolution of calcite accompanied by cation exchange alone.

The relationship between the value of the CMR, cation exchange and calcite saturation is best understood by understanding how cation exchange affects the equilibrium of the calcite dissolution reaction:

$$CaCO_3\,(s) + H^+\,(aq) \Leftrightarrow Ca^{2+}\,(aq) + HCO_3^-\,(aq) \qquad (4.2)$$

Cation exchange involves the exchange of Ca^{2+} ions for Na^+ ions at negatively charged exchange sites on suitable exchange media (e.g., montmorillonite clays). Therefore, Na^+ is added to the solution at the expense of Ca^{2+}. The removal of Ca^{2+} results in a shift to the right in Equation 4.2. This shift occurs in an attempt to reestablish the Ca^{2+} lost by cation exchange at the expense of calcite ($CaCO_3$). Dissolution continues as long as there is a source of calcite and H^+. The liberation of Na^+ and simultaneous removal of Ca^{2+} from solution generally results in an increase in the CMR, and an associated increase in HCO_3^- concentration and increase in pH, as cation exchange occurs.

Figure 19 also serves to illustrate both open and closed system paths for the dissolution of carbonate minerals (calcite and dolomite). Most surface and spring water samples plot relatively close together at a pH of slightly less than 7.0 and at a HCO_3^- concentration of about 10^{-3} mol/l. The spring waters have moderate CO_2 partial pressure (P_{CO2} rarely exceeds 10^{-2} atm.). Sample LC-7 is shown to be distinctly different from other spring samples and resembles groundwaters (GW) with high a high CMR (GW: CMR>20 in Fig. 8). It is likely that this spring water evolved along a pathway under closed-system conditions (i.e., depletion of

CO_2). This interpretation is consistent with the associated mineral dissolution described above. Because all waters with CMRs less than 3 fall below the calcite saturation line in Figure 19, we can conclude that cation exchange occurs both during dissolution of calcite and that calcite remains undersaturated. Similarly, those samples with a CMR greater than 3, but less than 20, plot near or slightly below the calcite saturation line. This suggests that cation exchange also occurs in the absence of calcite dissolution (so the Na/Ca ratio increases because Ca is not replaced). All samples with a CMR above 20 plot above the calcite saturation line. This suggests that both Na and Ca have increased (Na more than Ca) and that the water is supersaturated with respect to calcite, or that the calcite saturation lines are not appropriately placed and should shift to the right to accommodate a higher ionic strength solution.

4.1.3 Simple Mixing

The last major process discussed here that can influence the chemical evolution of groundwater is simple mixing, and particularly, its relevance to saltwater intrusion. Simple mixing involves combining two waters of different chemical, and sometimes, physical characters, without chemical reactions. The resulting composition is a hybrid of the two starting compositions. A common example of simple mixing involves the mixing of waters from different groundwater systems (e.g., shallow and deep). The net result is water with a new chemical composition that represents the different properties of the end member waters. Similarly, simple mixing can be is observed in association with salinization caused by active saltwater intrusion. During this process, saline groundwater, present at depth or intruded into the freshwater lens, mixes with fresh water. This process may be accelerated in certain areas by concentrated groundwater extraction from coastal aquifers.

Simple mixing is observed in many waters on Saturna Island. These waters typically plot along the bottom edge of the Piper diamond, and reflect different

percentages of mixing between water that has undergone cation exchange (Na-rich) and seawater (Cl-rich).

4.2 General Evolution of Groundwater

Groundwater on Saturna Island is generally observed to follow two linked primary evolutionary trajectories (Allen and Suchy, in press): 1) cation-exchange (Na enrichment), followed by, 2) simple mixing with Cl-rich water (salinization) (Figure 20). A secondary trajectory involves simple mixing of fresh groundwater (Ca-rich) and seawater (i.e., direct salinization without significant cation exchange), and is observed locally (e.g., East Point, Saturna Island).

Cation exchange followed by simple mixing appears to be the dominant evolutionary sequence on Saturna Island. Most sample groups exhibit strong cation exchange followed by salinization, while others display strong cation exchange alone (e.g., Tumbo Channel EP samples and MD samples) (refer to Piper plots in Appendix B).

4.2.1 Saltwater Intrusion

Contamination by saltwater appears to be present locally on Saturna Island. Because of the proximity of most wells to the coast, contamination is likely the result of saltwater intrusion. However, the mechanism of saltwater intrusion is unclear at this time.

Samples EP-6, EP-27(A,B,C,D), EP-29C, NB-3, MD-2 and LC-2 appear to have elevated EC and other dissolved constituents, characteristic of contamination by saltwater, and are characterized as saline groundwaters. Because most of these samples plot above seawater on the Piper plot (refer to Figure 15 and other Piper plots in Appendix B), it is likely that these wells are experiencing direct saltwater intrusion which is characterized by mixing of relatively fresh groundwater with ocean water. It is typical for water of this type to undergo a slight enrichment in

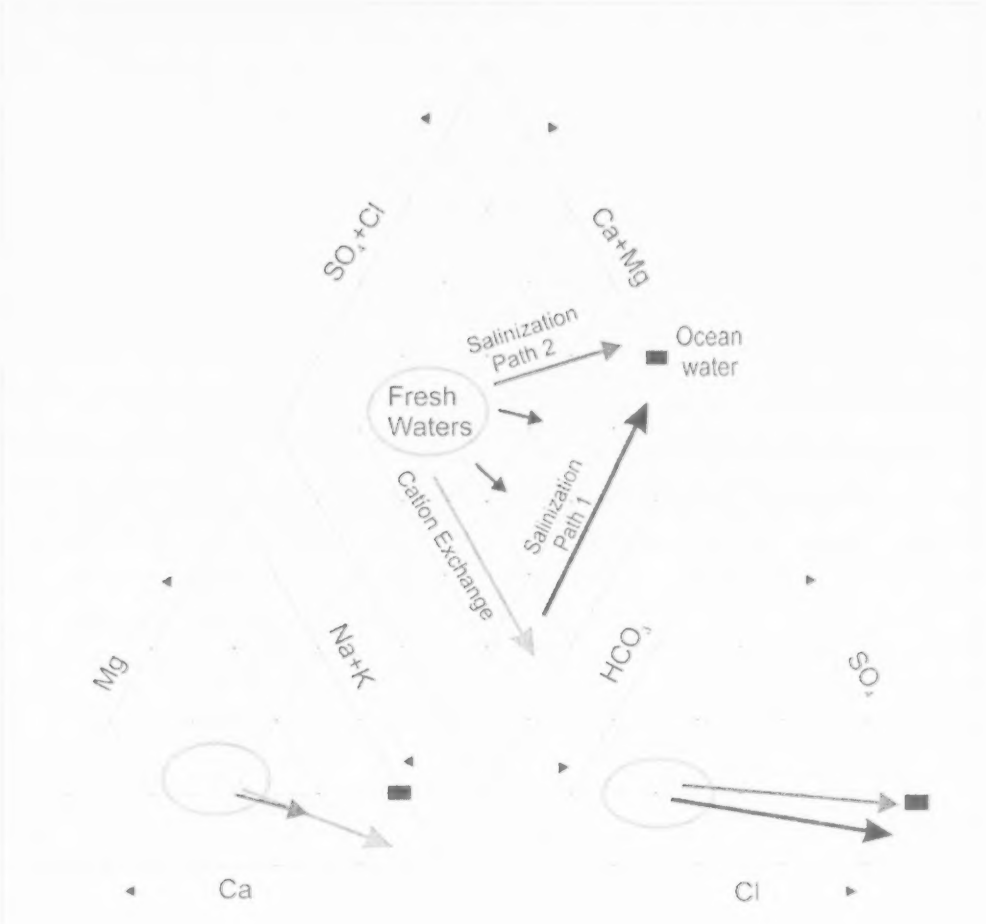


Figure 20: Generalized geochemical evolution of groundwater

Ca (in contrast to the enrichment in Na as described earlier) and to plot above the ocean water point on a Piper plot. Similarly, there are numerous other samples with elevated EC values and concentrations of dissolved constituents that suggest interaction with seawater. However, in these samples, the concentration of Na is significantly higher than in those samples mentioned above because of mixing of more evolved water types (Na-rich) with seawater.

Evidence in support of mixing of fresh groundwater with seawater and of mixing of slightly evolved groundwater with seawater is based upon several lines of supporting evidence: 1) Na/Cl ratios, 2) a Na-Cl bivariate plot, and 3) a log EC vs. log CMR plot.

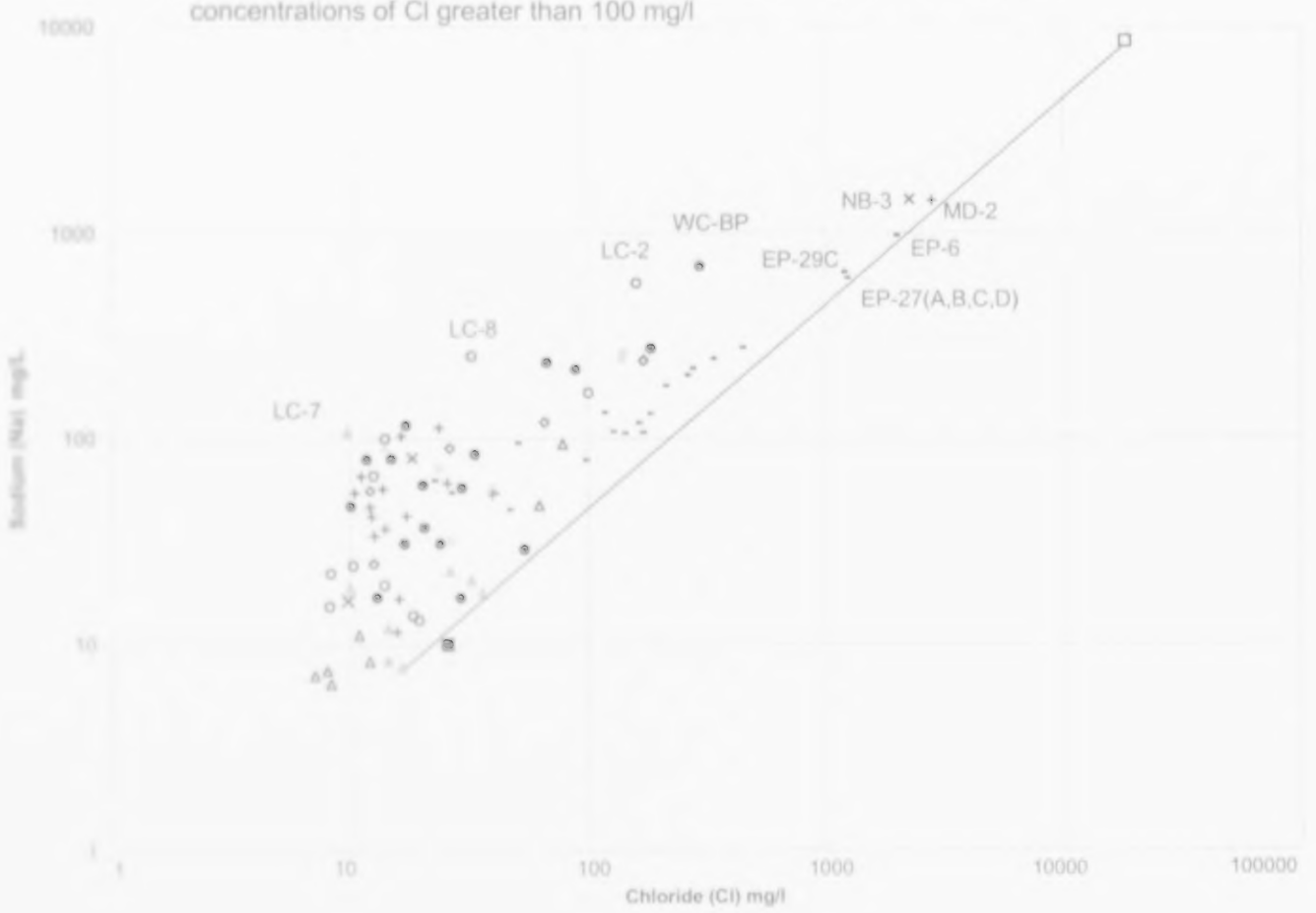
Firstly, Na/Cl ratios for the saline groundwater samples are very similar to that of the seawater sample CS-2 (Table 5). The slightly higher ratios, particularly for NB-3, can be directly attributed to the fact that groundwater of intermediate composition (i.e., with a high concentration of Na gained from cation exchange) mixes with seawater. Thus, the final Na/Cl ratio is slightly higher than if fresh groundwater had mixed with seawater.

Table 5. Summary of Na/Cl ratios for samples indicating contamination by saltwater

Sample ID	Na/Cl
EP-6	.763
EP-27A (B,C,D similar)	.769
EP-29C	.835
NB-3	.983
MD-2	.793
CS-2 (Seawater Control)	0.714

Secondly, the Na versus Cl plot (Figure 21) (and other similar plots with other constituents - see Suchy, 1998) demonstrates a that most samples on Saturna at

Figure 21: Bivariate plot for Na versus Cl. Seawater mixing line shown for concentrations of Cl greater than 100 mg/l

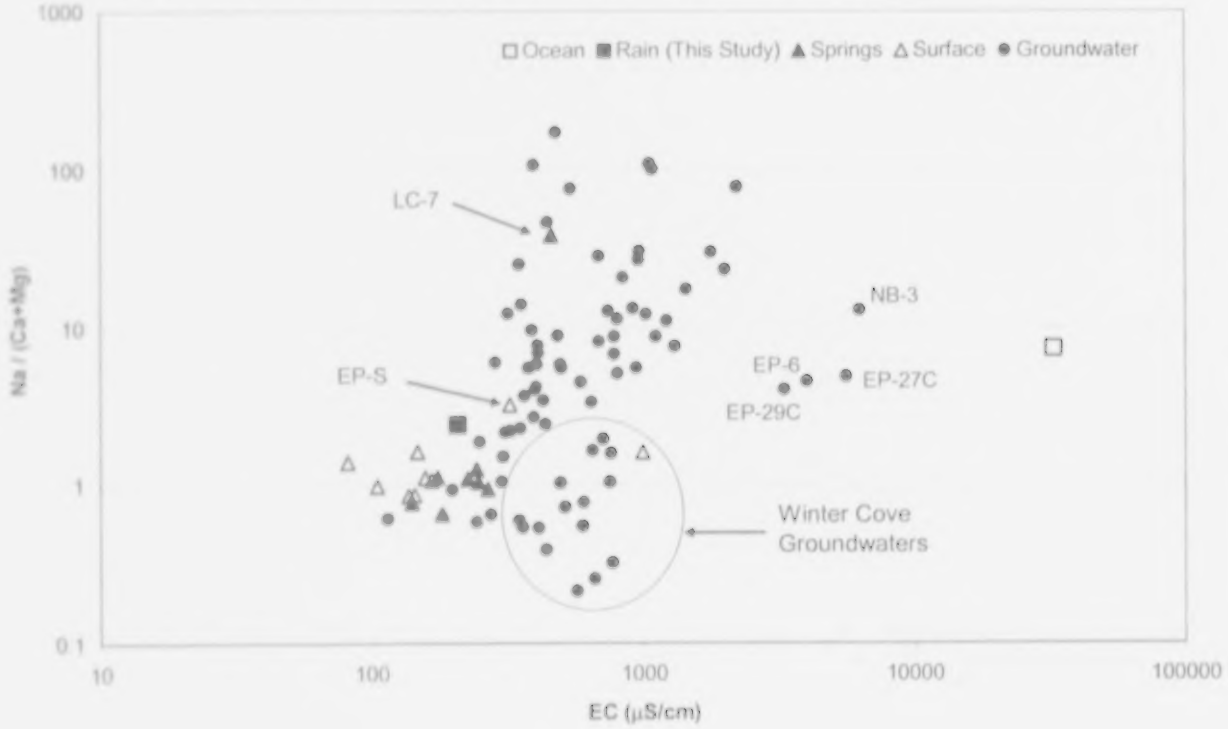


concentrations above about 100 mg/L Cl plot generally along but slightly above a mixing line between rain water and ocean water. Na is elevated in most samples for the reason of cation exchange as discussed above. Those samples with smaller percentages of Na-rich water mixing with seawater plot closer to the mixing line (e.g., NB-3, EP-27, EP-29C, MD-2, and EP-6).

The final line of evidence for contamination by saltwater is the independent relationship between log EC and the log CMR (Figure 22). High electrical conductivities are commonly associated with increased concentrations of the common anions Cl and SO_4^{2-}. If log EC is independent of log CMR the elevated CMR likely does not result from cation exchange. Rather, high CMRs probably the result of mixing of seawater and immature groundwater that has undergone little to no cation exchange.

East Point residents, as well as residents from other areas on Saturna, have experienced notable water quality and quantity degradation in recent years that is likely associated with salinization due to mixing of groundwater (both immature and intermediate in composition) with seawater according to the processes described above. Residents who previously had no problems with their water supplies have reported increases in turbidity, dry wells, lower yields, and a higher incidence of nitrate and bacterial contamination. Furthermore, there is a higher incidence of abandoned wells on East Point due to high salinity groundwaters, and many residents have opted to use rainwater collection systems in lieu of groundwater. As more lots become developed, there is a larger demand on groundwater resources. The demand is further compromised in the summer when precipitation is low and water use is high. Because of the low topographic relief and small catchment area, East Point peninsula also tends to receive less precipitation than adjacent flow regions. There are no permanent springs or seeps, and groundwaters have high Na/(Ca+Mg) ratios.

Figure 22: Cation molar ratio (Na / (Ca+Mg)) versus EC for Saturna waters.



The relation between distance along the peninsula and Cl^- and HCO_3^- is illustrated in Figures 23a and b. Most samples collected on the south shore show a distinct positive linear trend between Cl^-/HCO_3^- molar ratio and distance along East Point (from west to east) (Figure 23a). The presence of low ratios along the south shore is likely related to the occurrence of fractures. North shore ratios display no significant trend. Because Cl^- is present in very high concentrations, it is instructive to plot the inverse ratio HCO_3^-/Cl^- in a similar fashion (Figure 23b). Samples on the southern shore (EP-4, 5, 6, 27, 29, and 32) generally exhibit little variation in HCO_3^-/Cl^- with distance (open circles in Figure 23b), while samples from the northern shore (closed circles in Figure 23b) tend to exhibit a decrease in this ratio with distance along the peninsula. These relation not only suggest that the southern shore receives very little recharge, but that recharge likely occurs from higher elevation to the west (refer to Figure 2), and that inflow of fresh groundwater to East Point is restricted to the landward end of the peninsula.

To investigate whether there has been a measurable decline in water quality on East Point, the analyses from sample site EP-27 for 1983, 1986 and 1997 were compared. There is a substantial variation in the conductivity values measured in each of years 1983, 1986, and 1997; 1300 μS/cm, 5500 μS/cm and 4010 μS/cm, respectively. The significant increase between 1983 and 1986 lend support the conclusion salinization is prevalent along the south shore of East Point peninsula, but the subsequent decline between 1986 and 1997, suggests that perhaps seasonal variability associated with precipitation or sampling period may be a major factor controlling salinity.

The absence of fresh groundwaters and springs, and the high salinization of groundwater measured in this area are likely a result of the smaller flow region, and low local infiltration. The high elevation area to the west is likely the primary recharge zone for East Point groundwaters. The high EC of the swamp (EP-S)

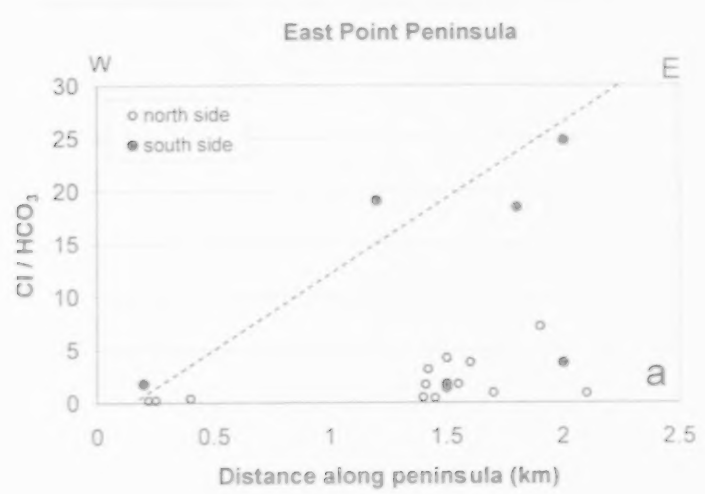


Figure 23a: Cl/HCO_3 molar ratio versus distance along East Point Peninsula (inland to coast)

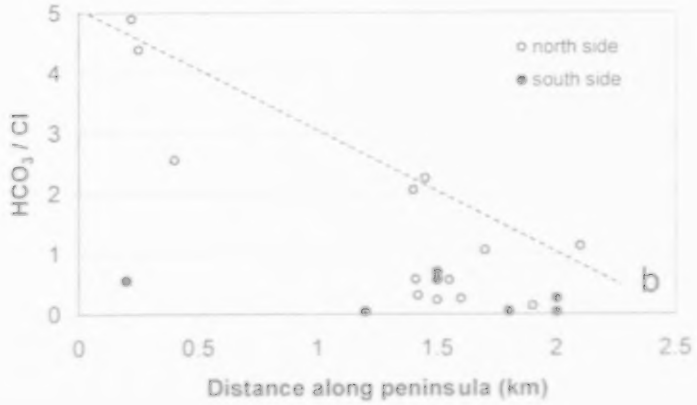


Figure 23b: HCO_3/Cl molar ratio versus distance along East Point Peninsula (inland to coast)

located in the central portion of the peninsula supports the conclusion that East Point is a discharge area. Furthermore, the long surrounding shoreline and finite land mass results in a limited fresh groundwater volume. These conditions suggest that freshwater reserves may be severely compromised by excessive groundwater withdrawal in this area.

4.2.2 Desalinization

Desalinization described here as an improvement in groundwater quality associated with a decrease in Cl^- concentration relative to HCO_3^-. An increase in HCO_3^-/Cl^- ratio with time would suggest flushing, and subsequent displacement or removal of saline groundwater. To illustrate that this process is likely occurring on Saturna Island, we will use the data from Winter Cove.

Winter Cove is comparatively a developed area of the island, but lot sizes are larger than those in similarly built-up areas (e.g., East Point peninsula). As a result, groundwater use in the Winter Cove Sub-Region is not as concentrated. Groundwaters collected from the northern properties (WC-4, 6, 7, 8, 9, 13, 14, 15, and WC-BP) are identified with open circles on the Piper plot (Figure 16), whereas samples collected from the southern properties are identified with closed circles (WC-1, 2, 3, 5, 10, 11, and 12). The southern samples, situated up geological dip (Figure 4), are generally more immature, as they have lower EC values. These waters plot similarly to other immature waters on the island, with the exception of WC-11 and WC-3. WC-11 was collected from a well that is approximately the same depth as other wells in Winter Cove. WC-3, with higher SO_4^{-2} than Cl^-, was collected from a very shallow well right near the coast. Most northern samples have Ca^{2+} as the dominant cation, which agrees with the conclusion that cation exchange does not appear to be a dominant process in the Winter Cove area. With the exception of WC-BP, these waters have moderate Cl^- and have significantly higher concentrations of SO_4^{-2} compared to most southern samples.

The limited amount of cation exchange in all of these waters could be explained by a lower residence time. More likely, it is the result of a low number of exchange sites on the predominantly sandstone units at depth. The cause of high sulphate concentrations is less obvious, but a similar groundwater composition was observed on Mayne Island (Dakin et al. 1983).

Trends in groundwater salinization in Winter Cove were investigated by comparing water analyses from 1981 with 1998. When the area was developed in the early 1980's, the chemistry for each well on every lot was analysed. Data from 12 wells are available for the two sampling times. The concentrations of major ions in 1998 are significantly lower than in 1981, with the exception that sulphate and calcium have generally increased in concentration. During the past 18 years, EC has decreased by as much as 500 μS/cm. Similarly, Na^+ and Cl^- concentrations have decreased by as much as 200 mg/L. Although Ca^{2+} has increased in concentration by as much as 90 mg/L, in general, concentrations have only changed by 50 mg/L. HCO_3^-/Cl^- is plotted against EC (Figure 24) to illustrate the overall trend. Samples exhibiting significant improvement (WC-4, 6, 11, and 14) are located on the north half of the sub-region. The likely cause of improved quality is groundwater flushing, which is evident as an increase in HCO_3^-/Cl^-. As this area was previously undeveloped, the groundwater system was closer to equilibrium because groundwater was not being extracted. With a lower circulation rate, the groundwater residence time was likely longer, and the potential for greater alteration due to chemical reactions like calcite dissolution increased. Since the land was put to residential use, the older more evolved groundwater has been pumped out, and younger water has replaced it. An interesting point is that groundwater samples taken from properties overlooking Lyall Harbour (south side) have only changed slightly or not at all. One possible reason for this is that natural groundwater circulation is probably down geological dip, and the up dip area might have been flushed before the development took place.

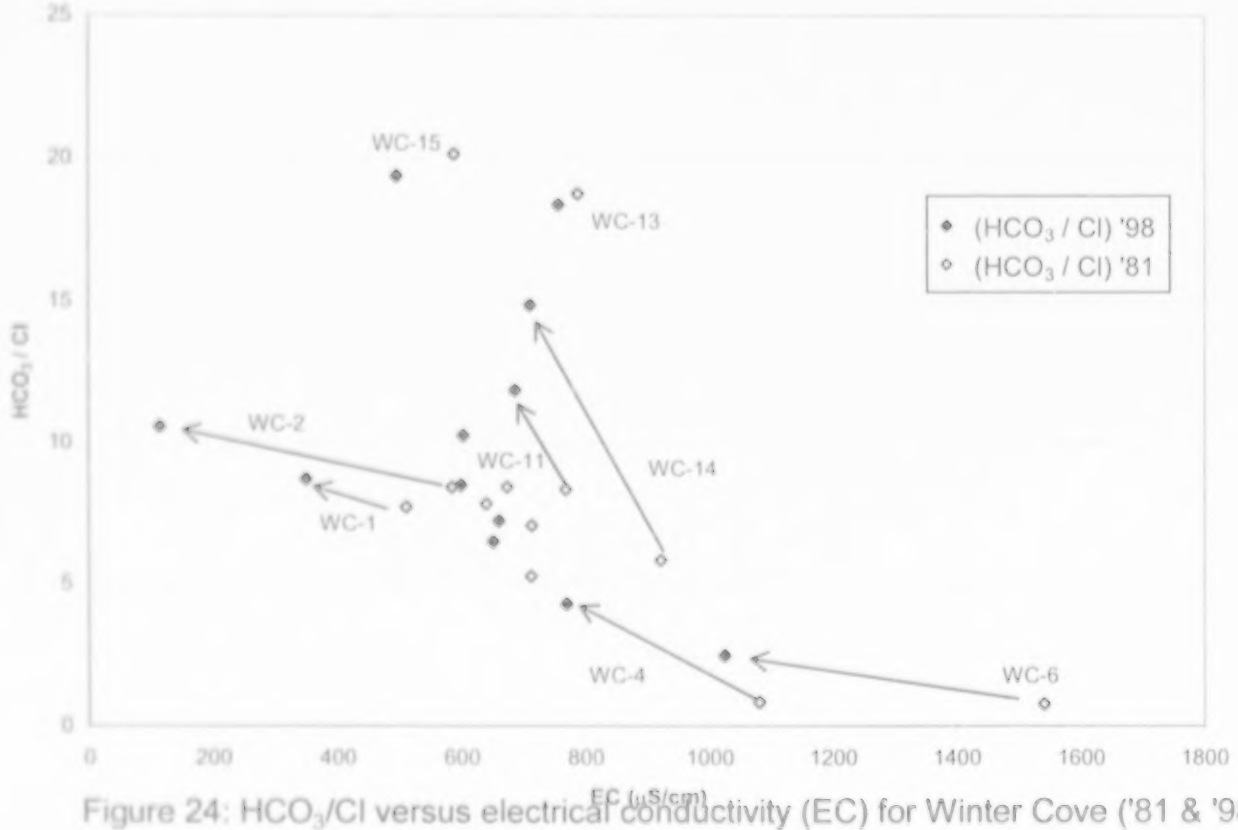


Figure 24: HCO_3/Cl versus electrical conductivity (EC) for Winter Cove ('81 & '98)

4.2.3 Origin of Dissolved Species

Specific sources of dissolved species, such as Na, Ca, Mg, Mn, F, Cl and SO_4, would require a detailed examination of not only the geology (by undertaking whole rock geochemistry), but also the geological history of the region. It is beyond the scope of work for this project to identify all the potential sources of dissolved species. However, the composition of groundwater is primarily a function of the geological units through which it flows, the residence time, the presence of mudstone units, the proximity to the ocean, the geological history, and possibly the depth of wells.

Understanding the origin of dissolved species is a focus of ongoing study. It is speculated that the many wells tap into saline water at depth, and that this saline water is coincident with the current freshwater-saltwater interface beneath the island. Over the past 10,000 years or so, following glacial rebound of the Gulf Islands, seawater has been flushed out of the islands, and has been largely replaced by relatively fresh water, particularly at high elevation. Because seawater is present at depth beneath all islands it is difficult to say if this is remnant seawater or present day seawater. The dynamics of this system are not fully understood, but are be the focus of ongoing research that will aim to model the rebound of the Gulf Islands and determine the equilibrium position of the freshwater-saltwater interface.

Regardless of the age of the saline water at depth, the chemistry of the groundwater for a large proportion of the wells indicates mixing with seawater. Furthermore, the observed distribution of dissolved constituents in groundwater, such as manganese, may be linked to the complex geological history of rebound, and may in fact, be associated with old seawater incursion.

4.3 Groundwater Flow Regions

As previously mentioned, the approach used to compare the analysis results was to divide the island into five flow regions. Two areas were separated into sub-regions, although they technically fell into other regions. The presence of distinct topographic differences, potential differences in precipitation, and likelihood for water anomalies formed the basis for this subdivision. For example, the Winter Cove Sub-Region is considered unique because of former land use (a dump and a shale plant), and East Point is considered unique because of the high density of lots and the proportionately small local potential recharge area.

For the most part, there is relatively good agreement between the flow regions determined on the basis of topography and those identified on the basis of the evolution of groundwater identified within each flow region. That is, we observe similar evolution trends on most of the Piper plots (see Appendix B), although some Piper plots clearly show only segments of the full evolutionary path.

Also, groundwater appears to evolve chemically from the higher elevation areas within each flow region to areas of lower elevation, although the results are skewed because the majority of the population, and thus, the ground water samples are from sites along the shoreline. Therefore, most samples represent groundwaters from discharge zones and very few from recharge areas or along groundwater flow paths. As a result, the sample distribution for Saturna might have a tendency to be more representative of the evolutionary end-product. Similarly, the presence of fracture zones in the subsurface act to complicate the evolution of water within each flow region and result in variations in the chemical composition of groundwaters sampled from nearby wells.

4.4 Recharge and Discharge Areas

Identifying groundwater recharge zones has strong implications in decisions regarding land use planning. Residential, agricultural and forestry development

within the headwaters of surface flow regions (watersheds) can potentially result in the degradation of both surface and groundwater quality and quantity.

Recharge and discharge areas represent zones of water input and output for groundwater systems. Typically, groundwater at discharge zones has a higher concentration of dissolved solids (higher TDS) compared to groundwater in recharge zones because of water-aquifer interactions and possible mixing with saline water along flow paths. Shallow residual (connate) groundwater is uncommon due to normal flushing of formation water by precipitation, particularly at high elevation, but may be present at depth in areas that are poorly flushed. Thus, groundwater tends to become increasingly saline with depth because of chemical interactions with aquifer materials, increased residence times, and mixing with older more mature groundwaters or possibly seawater. From an evolution perspective, groundwater in recharge zones will be immature while discharge zones will generally be more evolved. Areas in between recharge and discharge areas will generally have intermediate compositions. This type of pattern was observed on Saturna Island.

As well, the concentration of dissolved constituents can generally be linked to the flow paths (except perhaps for anomalous concentrations). The concentration contours shown in the maps for each dissolved constituent (Appendix C) generally outline the recharge areas (i.e., low concentrations are typically measured in these areas).

Working within this framework, the potential recharge and discharge areas that were identified earlier (Figure 8) are further supported on the basis of the chemistry. The outlines of the three recharge areas (two large ones over the main part of the island and a small on East Point peninsula) are rather extensive. This indicates that recharge occurs over a large percentage of the island and is not restricted to areas of high elevation (such as Mt. Warburton Peak).

It is important to recognize that rock type and the intensity of fracturing will play a role in determining if recharge occurs or does not occur at a local scale. Geological units that have very low porosity and have a low density of fractures will likely not support large amounts of recharge, although one large fracture can potentially offer a significant pathway for recharge. In contrast, mudstone units (such as the Northumberland Formation) and/or densely fractured sandstones offer ideal recharge areas.

Notwithstanding geological complexity, the overall movement of groundwater on the island is from high to low elevation. This conclusion is based not only on the groundwater chemistry results, but also the drilling data for the island which confirm that static water levels are higher at high elevation. Recharge from any other area (such as Vancouver Island) would require not only an upward hydraulic gradient so that deep wells would have higher static water levels than shallow wells both in the inland areas and along the coast, but also that there be no evidence of immature groundwater compositions nor an evolution of water chemistry that was continuous and complete on the island.

4.5 Geology as a Control on Groundwater Geochemistry

Aquifers on the Gulf Islands are characterized as fractured sedimentary bedrock aquifers. The low porosity of the sandstone and conglomerate units hint at a strong dependence on fracturing. This means that groundwater is much more likely to flow through fractures rather that through the porous matrix. This is not to say that there is no flow through unfractured bedrock, rather the majority of flow is accommodated by discrete flow paths.

The relative high permeability (due to high fracture intensity and interconnectivity) of mudstone units may cause groundwater to flow preferentially within these units. This conclusion is supported by Gulf Island water well drillers who generally find that principle water bearing units are at mudstone horizons. The

prevalence of a cation exchange process in most waters sampled in this study and on Saturna Island suggests that groundwater does move through units that contain significant amounts of clay. The widespread occurrence of cation exchange also hints that clay units are widespread, and are not necessarily restricted to mudstone-dominant formations (this is supported by the observation that many sandstone formations have mudstone horizons). Cation exchange was observed to be absent in predominantly sandstone formations (e.g., the de Courcy Formation on Saturna) (Allen and Suchy, in press).

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

- Groundwater on Saturna Island is recharged locally, typically at high elevation in areas corresponding to Mt. Warburton Peak, Mt. Fisher, Mt. David and Mt. Elford. However, the relatively immature chemical composition of many well waters (calcium-bicarbonate type water) situated at lower elevations suggests that recharge occurs over a significant portion of the island.
- Recharge in areas like East Point and Saturna Beach is limited as evidenced by the strong tendency toward salinization in wells situated in these areas.
- Groundwater flow regions originally defined on the basis of topography appear to coincide with chemical evolution trends identified in the sample groups employed for this study. However, many of the samples were collected from wells drilled near the coast, and therefore, may represent dominantly an end-type groundwater composition.
- Chemical evolution of groundwater on Saturna Island demonstrated cation exchange and salinization as dominant evolutionary pathways.
- Cation exchange (Ca exchanging for Na) is identified as a dominant geochemical process during the evolution of groundwater. In general, cation exchange was observed to be most prevalent in areas underlain by fine-grained sedimentary rocks. Therefore, it is suggested that groundwater flow through mudstone units may be the cause for the high occurrence of cation exchange. However, there was variability in this trend when sample groups containing different fine-grained formations were compared. This may suggest that cation exchange is dependent on the lithology encountered. Not all fine-grained units have the same ability to support cation exchange.
- Mature groundwaters, characterized by higher concentrations of chloride, result from mixing between the Na-rich groundwater and

saline groundwater at depth, associated with either modern seawater or remnant seawater. Several wells in the East Point area show significant salinization, and suggest that saltwater intrusion may be prevalent in that area.

- Areas with large variations in hydrochemistry might represent groundwater regimes controlled by fractures and/or faults. Some flow regions display significant changes in chemistry reflecting a combination of geologic differences, the presence of fractures that may act as conduits for flow, evolutionary trends in groundwater, and in limited cases, the onset of saltwater intrusion.

5.2 Recommendations

- Continue to collect and reevaluate groundwater geochemical data as a means of tracking potential trends in water quality. Observation of long-term patterns in groundwater geochemistry may allow for better understanding of the processes causing the changes. This type of exercise may be particularly useful for areas like East Point and in areas where development is increasing.
- Additional sampling of wells not sampled in this study may provide a higher resolution, and improved database, for future studies.
- Groundwater quality and quantity are of paramount importance to residents on Saturna Island and the other Gulf Islands. As such, water conservation, proper waste disposal and placement of human development should be made a priority in future land use planning. This should be done so as to protect sensitive groundwater recharge areas in upland locations.
- When residents perform periodic tests on their wells, it is important that analyses for chloride, sodium, calcium, magnesium, sulfate, alkalinity, pH, conductivity, and TDS should be made. This way, residents and

future studies can evaluate the evolution of groundwater on Saturna Island.

- For future wells drilled on the Gulf Islands the collection of detailed drill logs may allow for the collection of otherwise unobtainable subsurface geological controls on groundwater flow and evolution.
- The collection of whole rock geochemical analysis of samples of the fine-grained units (Northumberland and Spray Formations) and from fine-grained interbeds within the Geoffrey Formation may allow for the quantification of the differing cation exchange capacities of the different mud rich units underlying Saturna Island. Without this and other geologic data (e.g., structural data) a clear understanding of subsurface groundwater flow and evolution will be made extremely difficult.

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APPENDIX A

HYDROGEOCHEMICAL SUMMARY TABLE OF DATA COLLECTED FOR THIS STUDY

Test \ Sample ID			CS-1 *	CS-2 **	CS-3	BB-1	BB-2	BB-3	BB-4
Source / Depth		m	Distilled	Ocean	Rain	Spring	Spring	Well	Well
Conductivity		µS/cm	3.3	32800	208	247	141	301	429
Hardness		$CaCO_3$	-	4947	18	78	47	102	70
Total Alkalinity		$CaCO_3$	3.3	220	9.8	118	50.2	156	213
Field Alkalinity		$CaCO_3$	15	45	24	135	48	177	201
pH (Field)			5.47	7.80	5.84	6.81	6.50	7.58	7.82
Temperature (Field)		°C	19.3	16	16.7	12.7	12.3	14.9	15.7
TDS (Field)			0	>1990	60	120	80	170	60
PCO_2 (Calculated) 10 *		bars	-1.84	-2.65	-1.79	-1.69	-1.75	-2.34	-2.45
Bicarbonate (Calculated)		HCO_3^-	4.2	248.1	11.6	141.4	60.2	185.9	253.0
ANIONS	Fluoride	F	<	<0.05	<	0.07	<	0.07	0.13
	Chloride	Cl	<	18400	25.8	10	14.5	12.6	12.2
	Nitrate	N	<	9.68	0.12	<	0.13	0.3	<
	Nitrite	N	<	-	<	<	<	0.002	<
	Sulphate	SO_4	<	2150	5.4	21.8	15.2	19.4	25.4
	Total Phosphorus	PO_4	-	-	-	-	-	-	-
CATIONS	Aluminum	Al	<	<	0.043	0.009	0.007	0.007	0.008
	Antimony	Sb	<	<	<	<	<	<	<
	Arsenic	As	<	<	0.002	<	<	<	<
	Barium	Ba	<	0.008	0.006	0.028	0.009	0.14	0.003
	Beryllium	Be	<	<	<	<	<	<	<
	Boron	B	<	2.86	0.1	0.15	0.07	0.13	0.22
	Cadmium	Cd	<	<	<	<	<	<	<
	Calcium	Ca	<	385	4.29	24.3	13.7	37.3	21.4
	Chromium	Cr	<	<	<	<	<	<	<
	Cobalt	Co	<	<	<	<	<	<	<
	Copper	Cu	<	<	0.071	0.001	0.003	0.004	0.017
	Iron	Fe	<	0.06	0.87	<	0.05	<	<
	Lead	Pb	<	<	<	<	<	<	<
	Magnesium	Mg	<	996	1.8	4.4	3.14	2.24	4.08
	Manganese	Mn	<	0.008	0.072	0.006	0.03	0.064	<
	Molybdenum	Mo	<	<	<	0.001	<	0.01	<
	Nickel	Ni	<	<	0.003	<	0.001	<	<
	Phosphorus	PO_4	<	1.9	0.2	0.04	0.02	0.02	0.03
	Potassium	K	<	362	1.65	0.53	0.76	0.51	0.26
	Selenium	Se	<	-	<	<	<	<	<
	Silicon	SiO_2	<	3.2	0.84	9.15	9.17	8.69	8.7
	Silver	Ag	<	<	<	<	<	<	<
	Sodium	Na	<	8530	10	18.8	8.36	24.6	55.7
	Strontium	Sr	<	6.38	0.023	0.21	0.11	0.65	0.22
	Tellurium	Te	<	-	<	<	<	<	<
	Thallium	Tl	<	-	<	<	<	<	<
	Thorium	Th	<	-	<	<	<	<	<
	Tin	Sn	<	<	<	<	<	<	<
	Titanium	Ti	<	<	0.001	<	<	<	<
	Uranium	U	<	-	<	<	<	<	<
	Vanadium	V	<	<	<	<	<	<	0.002
	Zinc	Zn	<	<	0.16	0.052	0.077	0.14	0.12
	Zirconium	Zr	<	<	<	<	<	<	<

* Samples discarded due to extremely large charge balance errors
** Sample will be used for analysis, but will be deemed suspect if they plot as outliers
*** Samples not further used because of duplication of sample site

	BB-5	BB-S *	BR-1	BR-2	BR-S	EP-1	EP-2	EP-3	EP-4	EP-5
Depth	244	Swamp	198	198	Swamp	Well	81	85	93	72
Cond	409	68.2	319	351	137	588	1307	916	781	802
Hard	50	23	-	15	36	76	141	60	68	46
T. Alk	237	30.9	116	141	47.5	158	117	81.9	147	137
F. Alk	246	33	117	165	48	171	135	75	126	147
pH	8.06	6.49	8.76	9.04	7.49	7.66	8.19	8.35	7.74	8.24
Temp	15.6	14.2	13.9	13.3	12.3	15	15.2	14.7	14.8	15.6
TDS	250	40	10	170	50	350	550	480	440	450
PCO_2	-2.65	-1.95	-3.68	-3.90	-2.77	-2.43	-3.11	-3.42	-3.16	-3.07
HCO_3	279.7	36.2	129.7	149.9	56.2	188.0	135.8	94.4	170.4	160.2
F	0.25	<	0.23	0.28	<	0.15	0.16	0.26	0.15	0.16
Cl	26.4	3.3	39.9	14.1	7.1	96.6	332	209	141	161
N	<	<	<	<	0.22	<	<	<	<	<
N	<	0.004	<	0.007	0.004	<	<	<	<	<
SO_4	16.2	2.3	32.2	32.9	4.0	25.9	33.8	48	31.7	21.8
PO_4	-	-	-	-	-	-	-	-	-	-
Al	0.008	0.11	0.008	0.071	0.056	0.014	0.006	0.006	<	<
Sb	<	<	<	0.004	<	<	<	<	<	<
As	<	<	<	0.014	<	0.001	0.001	<	<	<
Ba	0.002	0.007	<	0.001	0.003	0.002	0.004	0.003	0.004	0.002
Be	<	<	<	<	<	<	<	<	<	<
B	0.24	0.11	0.91	0.35	0.1	0.43	0.53	0.71	0.47	0.43
Cd	<	<	<	<	<	<	<	<	<	<
Ca	14.3	6.64	8.2	4.84	10.6	25.7	47.2	22.8	21	16.1
Cr	<	<	<	<	<	0.001	<	<	0.001	<
Co	<	<	<	<	<	<	<	<	<	<
Cu	0.02	0.005	0.001	0.005	0.001	0.006	0.002	<	0.002	0.003
Fe	<	0.63	<	<	0.48	0.14	0.24	<	0.12	<
Pb	0.001	<	<	<	<	<	<	<	<	<
Mg	3.65	1.71	<	0.78	2.39	2.87	5.65	0.65	3.84	1.35
Mn	0.006	0.02	0.001	0.008	0.038	0.086	0.042	0.014	0.091	0.018
Mo	0.002	<	0.086	0.008	<	<	<	0.003	0.001	0.001
Ni	<	0.001	<	0.002	<	0.001	<	<	0.002	0.002
PO_4	0.06	0.3	<	0.04	0.07	0.08	0.09	0.06	0.09	0.05
K	0.27	0.58	0.12	0.62	0.31	0.52	0.91	0.29	0.71	0.4
Se	<	<	<	<	<	<	<	<	<	<
SiO_2	10.8	4.19	6.5	12.0	9.67	10.5	8.67	8.42	9.29	9.28
Ag	<	<	<	<	<	<	<	<	<	<
Na	89.9	3.8	57.8	88.7	7.09	78.4	246	181	106	119
Sr	0.18	0.057	0.019	0.051	0.072	0.14	0.23	0.11	0.12	0.094
Te	<	<	<	<	<	<	<	<	<	<
Tl	<	<	<	<	<	<	<	<	<	<
Th	<	<	<	<	<	<	<	<	<	<
Sn	<	<	<	<	<	<	<	<	<	<
Ti	<	0.003	<	0.002	0.004	<	<	<	<	<
U	<	<	<	0.0005	<	<	<	<	<	<
V	0.001	<	<	0.004	<	0.001	<	<	<	<
Zn	1.09	0.084	0.14	0.008	0.079	0.15	0.23	0.17	0.062	0.057
Zr	0.002	0.002	<	0.001	<	<	0.002	0.002	<	<

	EP-6	EP-7	EP-8	EP-9 **	EP-10	EP-11	EP-12	EP-13	EP-14	EP-15
Depth	87	40	122	131	Well	Spring	111	79	Spring	107
Cond	5590	485	390	357	353	175	400	198	182	325
Hard	868	46	30	17	79	46	57	53	51	72
T. Alk	148	155	195	181	149	40.4	152	47.8	71.4	158
F. Alk	177	70	180	237	171	54	198	60	84	174
pH	6.89	8.50	8.64	8.35	7.26	6.76	8.01	6.19	6.34	7.67
Temp	13.6	12	17.2	19	21.8	18.3	17.3	15.2	17.5	12.2
TDS	>1990	280	220	160	200	90	180	100	80	190
PCO_2	-1.76	-3.29	-3.32	-3.04	-2.02	-2.09	-2.78	-1.46	-1.43	-2.43
HCO_3	176.8	178.5	220.6	211.0	178.0	48.2	179.4	57.3	85.7	188.3
F	0.08	0.5	0.28	0.17	0.08	0.06	0.15	<	<	0.13
Cl	1960	50.4	11.2	10.5	17.3	14.5	39.9	15.8	16.5	14.1
N	1.2	0.6	<	<	0.2	1.8	<	3.6	<	<
N	<	-	<	<	<	<	<	<	0.024	<
SO_4	65.6	34.5	20.3	18.9	24.3	18.9	16.6	15	4.7	13
PO_4	-	0.014	-	-	-	-	-	-	-	-
Al	0.02	0.03	<	<	0.007	0.037	<	0.008	<	<
Sb	<	<	<	<	<	<	<	<	<	<
As	0.003	0.002	<	<	<	<	<	<	0.002	<
Ba	0.37	0.002	<	<	0.001	0.003	0.002	0.005	0.006	0.001
Be	<	<	<	<	<	<	<	<	<	<
B	0.41	0.28	0.59	0.44	0.21	0.11	0.39	0.14	0.11	0.27
Cd	<	<	<	<	<	<	<	<	<	<
Ca	282	16.2	9.88	5.87	28.2	12.8	21.2	15.2	15.8	25.6
Cr	<	<	<	<	<	<	<	<	<	<
Co	0.002	<	<	<	<	<	<	<	<	<
Cu	0.007	<	0.014	0.02	0.098	0.009	<	0.086	0.003	0.005
Fe	0.72	0.03	<	<	<	<	0.1	<	0.13	<
Pb	<	<	<	0.004	0.001	<	<	<	<	<
Mg	40.8	1.48	1.2	0.53	2.24	3.6	1.12	3.84	2.98	1.92
Mn	0.68	0.007	0.001	0.004	0.002	0.002	0.035	0.008	0.027	0.058
Mo	<	<	<	<	0.002	<	0.002	<	<	0.002
Ni	0.003	<	0.001	<	<	0.001	0.002	0.002	<	<
PO_4	0.05	<	0.36	0.06	0.07	0.06	0.07	0.06	0.03	0.06
K	7.04	0.8	0.34	0.24	0.4	0.7	0.36	0.64	1.06	0.36
Se	0.008	-	<	<	<	<	<	<	<	<
SiO_2	14.3	12.9	10.6	8.94	11.5	13.9	9.57	14.9	13.1	9.71
Ag	<	<	<	<	<	<	<	<	<	<
Na	974	95	65.3	54.3	41.9	12	53.2	11.5	7.76	36.4
Sr	2.43	0.1	0.074	0.044	0.075	0.1	0.091	0.1	0.098	0.11
Te	<	-	<	<	<	<	<	<	<	<
Tl	<	-	<	<	<	<	<	<	<	<
Th	<	-	<	<	<	<	<	<	<	<
Sn	<	<	<	<	0.006	<	<	<	<	<
Ti	0.003	<	<	<	0.001	0.003	<	<	<	<
U	0.0006	-	<	<	<	<	<	<	<	<
V	0.004	<	<	<	<	<	<	<	<	<
Zn	0.005	<	0.029	0.065	0.072	0.006	<	0.041	<	0.099
Zr	0.003	<	<	<	<	<	<	<	<	<

	EP-16	EP-17	EP-18	EP-19	EP-20	EP-21	EP-22	EP-23	EP-24	EP-25 *
Depth	107	67	Well	38	107	60	107	110	76	158
Cond.	406	781	841	436	1110	803	286	379	404	565
Hard	45	54	-	80	109	91	30	43	56	63
T. Alk	169	193	149	150	127	143	145	169	151	96.6
F. Alk	186	210	156	165	150	165	126	189	165	90
pH	8.01	7.58	8.07	7.07	8.13	8.10	7.81	8.19	8.13	8.30
Temp	19.1	14.1	17.1	13.8	17.2	13.3	14.6	15.5	13.1	15.5
TDS	230	460	530	250	670	440	170	210	200	240
PCO_2	-2.73	-2.26	-2.86	-1.86	-3.01	-2.92	-2.60	-2.92	-2.92	-2.78
HCO_3	199.5	230.2	175.7	179.3	148.2	168.1	172.5	198.5	177.7	113.9
F	0.2	0.14	0.19	0.16	0.15	0.18	0.09	0.27	0.27	0.39
Cl	25.8	126	180	46.2	272	168	12.4	26.3	40.4	46.8
N	<	<	<	<	<	<	<	<	<	<
N	<	<	<	<	<	<	<	<	<	-
SO_4	18.1	34.8	18.2	23.2	29.4	16.8	12.2	13.2	15.5	35.5
PO_4	-	-	-	-	-	-	-	-	-	0.011
Al	<	<	<	0.049	<	<	0.007	<	0.007	0.088
Sb	<	<	<	<	<	<	<	<	<	<
As	<	<	<	0.001	0.001	<	0.001	<	<	0.001
Ba	0.001	0.002	<	0.003	0.004	0.003	0.002	0.001	0.002	0.003
Be	<	<	<	<	<	<	<	<	<	<
B	0.45	0.63	0.77	0.3	0.5	0.48	0.2	0.45	0.45	0.37
Cd	<	<	<	<	<	<	<	<	<	<
Ca	17	19.9	11.1	25	39.1	31.7	10.9	15.2	19.3	22.1
Cr	<	<	<	<	<	<	<	<	<	<
Co	<	<	<	<	<	<	<	<	<	<
Cu	0.002	<	0.013	0.039	0.001	0.002	0.092	0.003	0.003	<
Fe	<	0.1	<	0.29	<	<	<	0.23	<	0.09
Pb	<	0.002	0.002	<	<	<	0.006	<	<	<
Mg	0.65	0.96	<	4.42	2.87	2.98	0.72	1.19	1.91	1.84
Mn	0.022	0.037	0.004	0.081	0.04	0.054	0.035	0.023	0.025	0.033
Mo	0.005	0.002	0.001	<	<	<	<	0.004	0.002	<
Ni	<	<	<	0.001	<	<	<	<	<	<
PO_4	0.08	0.08	0.05	0.05	0.08	0.06	0.06	0.07	0.1	<
K	0.31	0.43	0.19	0.68	0.86	0.73	0.28	0.35	0.52	0.59
Se	<	<	<	<	<	<	<	<	<	-
SiO_2	9.14	11.9	8.11	10.8	8.29	8.68	9.82	8.97	8.86	17.1
Ag	<	<	<	<	<	<	<	<	<	<
Na	60.6	108	132	45	220	107	41.7	54.6	54	121
Sr	0.076	0.075	0.034	0.1	0.22	0.19	0.054	0.079	0.12	0.12
Te	<	<	<	<	<	<	<	<	<	-
Tl	<	<	<	<	<	<	<	<	<	-
Th	<	<	<	<	<	<	<	<	<	-
Sn	<	<	<	<	<	<	<	<	<	<
Ti	<	0.004	<	0.003	<	<	<	<	<	<
U	<	<	<	<	<	<	<	<	<	-
V	<	0.005	0.002	0.002	<	<	0.001	0.002	0.002	<
Zn	0.039	0.052	0.01	0.036	0.028	<	0.069	0.42	0.013	<
Zr	<	0.002	0.002	0.002	<	0.002	<	0.001	0.001	<

	EP-26A	EP-26B ***	EP-27A	EP-27B ***	EP-27C ***	EP-27D ***	EP-28A ***	EP-28B	EP-29A ***	EP-29B
Depth	107	107	110	110	110	110	152	152	68	68
Cond.	366	366	3300	4390	4010	3900	1530	1440	950	968
Hard	73	81	601	819	687	663	78	69	29	29
T. Alk	159	160	140	126	122	119	76.2	88.2	102	101
F. Alk	64	75	53	53	51	51	34	31	38	39
pH	7.70	7.80	9.70	7.90	7.80	7.80	7.60	7.60	8.50	8.30
Temp	13.5	13.5	14	15	13.5	14.5	13	14	14	12.5
TDS	210	230	1850	>1990	>1990	>1990	970	870	600	510
PCO_2	-2.46	-2.57	-5.02	-2.85	-2.75	-2.76	-2.70	-2.64	-3.48	-3.28
HCO_3	188.6	189.3	59.0	145.9	142.7	139.3	90.6	104.9	116.7	117.6
F	<	<	0.1	0.1	0.11	0.12	<	<	0.78	0.79
Cl	22.4	22.2	1210	1730	1530	1490	467	439	258	258
N	<	<	<	0.64	0.64	0.66	<	<	<	<
N	-	-	-	-	-	-	-	-	-	-
SO_4	16.5	16.4	186	228	209	213	64.8	53.8	34.6	34.4
PO_4	-	0.015	0.007	-	-	-	0.002	-	0.011	0.011
Al	0.09	0.09	0.018	0.018	0.018	<	0.015	0.015	0.01	0.01
Sb	<	<	<	<	<	<	<	<	<	<
As	<	0.001	0.002	0.002	0.002	<	<	<	<	<
Ba	0.004	0.005	0.1	0.15	0.12	0.11	0.013	0.034	0.002	0.002
Be	<	<	<	<	<	<	<	<	<	<
B	0.11	0.11	0.41	0.55	0.53	0.53	0.78	0.82	0.69	0.7
Cd	<	<	<	<	<	<	<	<	<	<
Ca	22.9	25.1	169	227	193	185	29.7	26.1	10.2	10.3
Cr	<	<	<	<	<	<	<	<	<	<
Co	<	<	<	<	<	<	<	<	<	<
Cu	<	<	<	<	<	<	<	<	<	<
Fe	0.11	0.18	0.03	<	<	<	2.32	0.59	<	<
Pb	<	<	<	<	<	<	<	<	<	<
Mg	4.06	4.46	44.6	62.8	51.1	50.1	1.03	1.03	0.84	0.84
Mn	0.067	0.081	0.28	0.42	0.35	0.33	0.12	0.16	0.01	0.017
Mo	<	<	<	<	<	<	<	<	<	<
Ni	<	<	<	<	<	<	<	<	<	<
PO_4	<	<	0.4	<	<	<	<	<	<	<
K	0.58	0.53	4.28	5.22	4.52	4.49	0.56	0.6	0.52	1.21
Se	-	-	-	-	-	-	-	-	-	-
SiO_2	15.8	16.2	18.2	17.6	17.7	17.5	11.8	12.2	14.1	14.2
Ag	<	<	<	<	<	<	<	<	<	<
Na	62.5	62.4	606	804	722	712	287	278	201	204
Sr	0.12	0.13	1.3	1.81	1.54	1.47	0.19	0.18	0.036	0.035
Te	-	-	-	-	-	-	-	-	-	-
Tl	-	-	-	-	-	-	-	-	-	-
Th	-	-	-	-	-	-	-	-	-	-
Sn	<	<	<	<	<	<	<	<	<	<
Ti	0.007	<	<	<	<	<	<	0.009	<	<
U	-	-	-	-	-	-	-	-	-	-
V	<	<	<	<	<	<	<	<	<	<
Zn	<	<	<	<	<	<	1.55	0.23	<	<
Zr	<	<	<	<	<	<	<	<	<	<

	EP-29C ***	EP-30	EP-31	EP-32	EP-S	LC-1	LC-2	LC-3	LC-4	LC-5
Depth	68	91	122	151	Swamp	40	44	Creek	61	49
Cond	3310	310	250	540	324	569	2220	148	941	396
Hard	697	93	78	8	63	282	32	43	130	106
T. Alk	90.3	132	111	125	48.3	291	331	47.2	246	190
F. Alk	44	135	102	144	29	285	360	20	249	216
pH	8.10	7.30	7.92	9.43	6.60	7.16	8.93	7.70	7.85	7.96
Temp	13.5	12.6	13.2	11.3	19	16.2	16.1	17	17.6	16.3
TDS	1190	150	120	280	200	240	1270	70	480	220
PCO_2	-3.19	-2.14	-2.84	-4.43	-1.88	-1.67	-3.48	-2.97	-2.43	-2.65
HCO_3	102.8	157.7	131.3	110.9	55.9	347.7	333.5	56.1	290.6	224.1
F	0.32	<	0.08	4.1	0.045	0.09	0.92	<	0.23	0.14
Cl	1180	12.2	12.7	116.0	62.7	18.4	161	9.8	101	12.6
N	<	0.05	<	<	<	0.31	0.16	0.26	<	<
N	-	<	<	<	-	<	0.007	-	<	<
SO_4	184	24.5	25.5	1.5	27.8	40.4	671	14.7	124	27.3
PO_4	0.011				0.24	-	-	0.02		
Al	0.01	0.015	0.007	0.018	0.3	0.007	<	<0.2	0.008	0.011
Sb	<	<	<	<	<	<	<	<	<	<
As	<	<	0.001	<	<	0.007	0.003	<	0.002	0.012
Ba	0.012	0.002	0.002	0.003	0.019	0.017	0.015	0.008	0.08	0.034
Be	<	<	<	<	<	<	<	<	<	<
B	0.82	0.18	0.44	2.56	0.05	0.15	10.4	0.04	2.28	0.46
Cd	<	<	<	<	<	<	<	<	<	<
Ca	212	31.2	25.9	2.91	13.3	90.7	11.6	11.7	38.3	31.6
Cr	<	<	<	<	<	<	0.001	<	<	<
Co	<	<	<	<	<	<	<	<	<	<
Cu	<	0.011	0.004	0.001	<	0.007	0.006	<	0.006	0.001
Fe	<	0.05	<	<	1.78	0.08	<	0.1	0.11	0.06
Pb	<	<	0.006	<	<	<	<	<	<	<
Mg	41.8	3.76	3.26	0.11	7.39	13.8	0.81	3.54	8.65	6.66
Mn	0.16	0.006	0.011	0.005	0.074	0.041	0.028	0.01	0.21	0.021
Mo	<	0.003	0.002	0.002	<	<	0.002	<	<	<
Ni	<	0.001	0.001	<	<	0.001	<	<	0.001	<
PO_4	<	0.04	<	0.12	0.5	0.04	0.16	<	<	<
K	1.81	0.61	0.17	0.37	1.43	1.43	1.02	0.68	2.21	5.74
Se	-	<	<	<	-	<	<	-	<	<
SiO_2	14.4	15.3	14.1	10.1	25.9	10.7	5	18	11.5	20.0
Ag	<	<	<	<	<	<	<	<	<	<
Na	648	46.2	33.6	134	47.2	13.8	574	16.3	167	65.7
Sr	1.16	0.1	0.076	0.021	0.11	0.76	0.39	0.079	0.76	1.12
Te	-	<	<	<	-	<	<	-	<	<
Tl	-	<	<	<	-	<	<	-	<	<
Th	-	<	<	<	-	<	<	-	<	<
Sn	<	<	<	<	<	<	<	<	<	<
Ti	<	<	<	<	<	<	<	<	<	<
U	-	<	<	<	-	<	<	-	<	<
V	<	<	<	<	<	<	<	<	<	<
Zn	<	0.013	0.69	<	<	0.14	<	<	0.009	<
Zr	<	<	<	0.015	<	<	0.005	<	<	<

	LC-6	LC-7	LC-8	MD-1	MD-2	MD-3	MD-4	MD-5	MD-S *	ML-1 *
Depth	49	Spring	61	17	56	Well	Well	5	Swamp	Lake
Cond.	275	460	1054	397	7410	411	412	445	88	158
Hard.	129	12	10	5	493	36	135	10	39	68
T. Alk.	123	247	351	197	94.2	193	179	205	27.3	59.8
F. Alk.	147	276	-	195	111	204	201	201	15	31
pH	6.57	8.93	9.23	7.61	8.05	9.24	7.18	9.36	6.40	6.80
Temp	12.3	18.1	11.6	14.6	13.5	13	11.7	12.4	18	19
TDS	140	250	470	210	>1990	190	200	220	50.0	80
PCO_2	-1.44	-3.53	-3.75	-2.27	-3.14	-3.99	-1.89	-4.11	-1.92	-1.96
HCO_3	147.4	266.9	344.8	2344.0	108.3	193.6	214.0	192.3	31.7	71.7
F	0.05	0.21	4.3	0.44	0.68	0.17	0.07	1.8	<0.05	<0.05
Cl	14.0	9.8	32.7	23.8	2800	13.8	16.1	16.5	8.4	11.5
N	<	0.07	0.13	<	0.69	<	0.16	<	<	<
N	<	<	0.004	<	<	<	<	0.005	-	-
SO_4	13.8	20.5	178	13.0	5.3	13.5	20.6	19.1	7.2	7.2
PO_4		-	-	-	-	-	-	-	0.04	0.026
Al	0.013	0.031	0.01	0.084	0.01	0.045	0.008	0.033	<	<0.2
Sb	<	<	<	<	<	<	<	<	<	<
As	<	0.002	0.004	<	0.005	<	0.001	0.011	<	<
Ba	0.018	0.004	0.01	0.003	1	0.006	0.006	0.002	0.002	0.004
Be	<	<	<	<	<	<	<	<	<	<
B	0.2	0.87	5.2	1.03	1.33	0.34	0.06	3.27	0.02	0.02
Cd	<	<	<	<	<	<	<	<	<	<
Ca	36	3.61	3.4	1.52	181	10.6	41.2	3.04	8.62	18.1
Cr	<	<	<	<	<	<	<	<	<	<
Co	<	<	<	<	<	<	<	<	<	<
Cu	0.005	0.004	0.002	0.001	0.001	0.002	<	0.002	<	<
Fe	0.11	<	<	0.11	0.81	<	<	0.06	0.38	0.5
Pb	<	<	<	<	<	<	<	<	<	<
Mg	9.86	0.78	0.4	0.2	10.1	2.25	8.1	0.5	4.28	5.67
Mn	0.15	0.004	0.006	0.01	0.14	0.19	0.004	0.027	0.017	0.43
Mo	<	0.001	<	0.009	0.004	0.001	0.002	0.009	<	<
Ni	0.004	<	<	0.002	0.003	<	<	0.001	<	<
PO_4	0.02	0.13	0.08	0.16	0.01	<	<	0.01	1.9	<
K	1.32	0.24	0.9	0.56	2.64	1.06	0.96	0.25	0.3	0.97
Se	<	<	<	<	<	<	<	<	-	-
SiO_2	20.2	12.5	8.2	11.8	6.26	9.34	8.5	7.4	4.5	19.7
Ag	<	<	<	<	<	<	<	<	<	<
Na	19.4	108	253	113	1440	56.6	16.6	103	24	17.5
Sr	0.24	0.034	0.1	0.02	4.09	0.11	0.28	0.027	0.088	0.15
Te	<	<	<	<	<	<	<	<	-	-
Tl	<	<	<	<	<	<	<	<	-	-
Th	<	<	<	<	<	<	<	<	-	-
Sn	<	<	<	<	<	<	<	<	<	<
Ti	<	0.002	<	0.006	<	0.005	<	0.002	<	<
U	<	<	<	<	<	<	<	<	-	-
V	<	<	<	0.001	<	<	<	<	<	<
Zn	0.009	<	0.022	<	<	0.005	0.006	<	<	0.03
Zr	<	<	0.01	0.007	<	<	<	0.008	<	<

	ML-2 **	NB-1	NB-2 *	NB-3	NB-4	NB-5	NB-6	NB-7	NB-8	NB-S
Depth	Lake	46	Creek	43	91	Well	91	Well	55	Swamp
Cond	144	495	246	6280	305	439	479	244	360	82.1
Hard	56	60	59	491	69	147	3	114	178	20
T. Alk	53.5	204	111	178	126	212	250	105	182	23.8
F. Alk	33	234	132	195	135	192	180	129	195	42
pH	6.60	7.68	7.89	8.18	7.05	7.20	9.54	6.88	6.82	6.81
Temp	16	18	16.3	17.5	16.6	13.3	13.3	17.2	11.6	20.9
TDS	90	290	140	>1990	150	220	260	120	170	40
PCO_2	-1.82	-2.33	-2.88	-2.68	-1.90	-1.84	-4.23	-1.81	-1.53	-2.36
HCO_3^-	63.5	242.8	109.4	207.2	150.8	253.6	222.4	125.7	218.0	28.5
F	<	0.1	0.17	3.5	0.08	0.13	0.23	0.12	0.08	<
Cl	10.9	18.3	84.9	2260	10.3	19.5	14.1	8.2	8.3	8.3
N	<	0.31	<	<	0.49	0.2	<	0.22	0.35	0.21
N	-	<	<	<	<	0.004	0.004	<	<	<
SO_4	6.1	40.3	26.1	91.6	19.7	15.9	34.2	19.2	15.3	6.8
PO_4	-	-	-	-	-	-	-			-
Al	<0.2	0.009	0.014	0.011	0.009	<	0.011	0.012	0.01	0.01
Sb	<	<	<	<	<	<	<	<	<	<
As	<	<	<	0.003	<	<	<	<	<	<
Ba	0.006	0.006	0.006	0.054	<	0.042	0.018	0.002	0.067	0.004
Be	<	<	<	<	<	<	<	<	<	<
B	0.02	0.38	0.26	0.93	0.1	0.11	0.3	0.19	0.21	0.09
Cd	<	<	<	<	<	<	<	<	<	<
Ca	15.8	19.6	15.6	160	20.6	43.4	0.85	32.1	52.6	5.45
Cr	<	<	<	<	0.002	<	0.001	<	<	<
Co	<	<	<	<	<	<	<	<	<	<
Cu	<	0.042	0.004	0.002	0.01	0.005	0.001	0.019	0.006	0.001
Fe	4.78	<	0.06	0.11	0.05	<	<	0.06	0.06	0.11
Pb	<	0.002	<	<	<	<	<	<	<	<
Mg	4.07	2.67	5.08	22.8	4.42	9.56	0.1	8.36	11.7	1.6
Mn	0.97	<	0.002	0.12	0.032	0.056	0.002	0.005	<	0.021
Mo	<	<	<	<	<	<	0.001	<	<	<
Ni	<	0.007	<	<	0.006	0.002	0.004	0.002	<	<
PO_4	1.1	0.06	0.08	0.05	0.05	0.04	0.11	0.05	0.03	0.02
K	1.09	0.37	0.94	1.76	0.11	0.49	0.14	0.34	0.42	0.19
Se	-	<	<	<	<	<	<	<	<	<
SiO_2	17.9	10.7	10.7	5.57	10.2	14.4	9.2	23.3	23.2	3.02
Ag	<	<	<	<	<	<	<	<	<	<
Na	11.1	80.4	25.7	1460	24.1	13.1	100	15.3	22.1	6.46
Sr	0.13	0.076	0.11	3.17	0.085	0.14	0.024	0.081	0.25	0.05
Te	-	<	<	<	<	<	<	<	<	<
Tl	-	<	<	<	<	<	<	<	<	<
Th	-	<	<	<	<	<	<	<	<	<
Sn	<	<	<	<	<	<	<	<	<	<
Ti	<	<	0.001	<	<	0.002	<	<	<	<
U	-	<	<	<	<	<	<	<	<	<
V	<	0.001	<	<	<	<	<	<	<	<
Zn	<	0.16	0.088	0.083	0.18	0.01	0.1	0.009	0.008	0.11
Zr	<	0.001	<	0.012	<	<	<	0.001	<	<

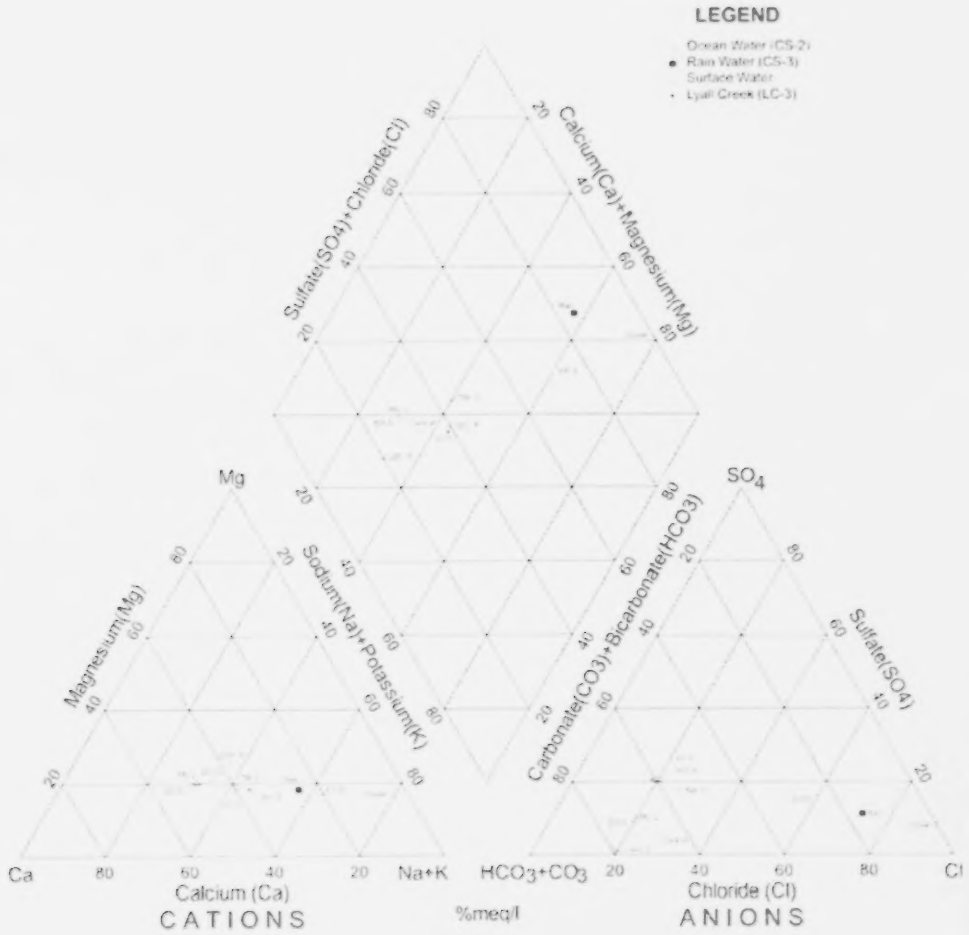
	OPF-1	OPF-2 **	OPF-P	SB-1	SB-2	SB-3	SB-4	SB-5	SB-6	SB-7
Depth	122	122	Pond	Well	Well	Well	52	Spring	Spring	Spring
Cond	958	685	166.4	error	error	499	515	244	268	226
Hard	39	18	33	46	38	56	193	78	94	71
T. Alk	220	262	43.5	307	309	232	232	71.2	77.3	41.4
F. Alk	255	279	66	264	270	213	219	46	43	25
pH	7.59	8.22	7.20	8.50	7.54	8.00	7.57	6.30	6.20	6.40
Temp	14.7	14.2	16.2	13.7	13.8	15.9	15.9	12.8	14	16
TDS	70	70	60	500	570	300	250	140	140	140
PCO_2	-2.30	-2.77	-2.50	-3.01	-2.03	-2.60	-2.17	-1.40	-1.27	-1.73
HCO_3	218.4	308	51.8	352.1	368.7	274.2	276	85.2	92.6	49.4
F	0.24	0.36	0.07	0.36	0.39	0.18	0.28	<0.05	<0.05	<0.05
Cl	172	66	12.1	140	143	23.7	26.6	26.4	32.4	36.1
N	<	<	<	<	<	<	0.66	0.38	<	0.29
N	<	<	<	0.002	0.033	<	<	-	-	-
SO_4	68.6	69.3	3.1	83.2	99.3	17.4	50.1	18.6	23.6	20.3
PO_4	-	-	-	-	-	-	-	0.027	-	-
Al	0.013	0.014	0.042	0.018	0.024	0.015	0.005	0.066	0.066	0.066
Sb	<	<	<	<	<	<	<	<	<	<
As	0.004	<	0.002	0.015	0.008	<	0.001	<	<	<
Ba	0.013	0.008	0.007	0.03	0.035	0.13	0.095	0.061	0.054	0.01
Be	<	<	<	<	<	<	<	<	<	<
B	1.02	0.93	0.07	1.77	1.9	0.43	0.22	0.05	0.03	0.03
Cd	<	<	<	<	0.0003	<	<	<	<	<
Ca	12.1	5.54	8	14.2	11.6	16.7	57.5	20.8	24.6	20
Cr	<	<	<	<	<	<	<	<	<	<
Co	<	<	<	<	<	<	<	<	<	<
Cu	0.075	0.006	0.009	0.001	0.004	0.003	0.002	<	<	<
Fe	<	<	0.55	0.06	<	<	0.06	0.03	<	0.04
Pb	0.002	<	<	<	<	<	<	<	<	<
Mg	2.08	1.11	3.36	2.71	2.36	3.51	12.4	6.5	8.24	5.14
Mn	0.014	0.008	0.11	0.064	0.11	0.08	0.015	0.004	0.006	0.011
Mo	<	0.001	0.006	0.002	0.003	<	<	<	<	<
Ni	0.002	<	0.003	0.001	0.002	<	0.001	<	<	<
PO_4	0.15	0.16	<	0.09	0.05	0.1	0.07	<	<	<
K	0.79	0.36	1.33	2.64	2.65	1.07	1.29	0.81	0.76	0.56
Se	<	<	<	<	<	<	<	-	-	-
SiO_2	7.92	5.07	0.46	9.63	7.39	14.7	17.4	19.6	25.1	14.5
Ag	<	<	<	<	<	<	<	<	<	<
Na	240	120	8.29	248	267	71.6	32.1	22.6	20.5	17.8
Sr	0.24	0.065	0.077	0.48	0.46	0.41	0.56	0.14	0.18	0.13
Te	<	<	<	<	<	<	<	-	-	-
Tl	<	<	<	<	<	<	<	-	-	-
Th	<	<	<	<	<	<	<	-	-	-
Sn	<	<	<	<	<	<	<	<	<	<
Ti	<	<	0.003	0.001	0.001	<	<	<	<	<
U	<	<	<	<	<	<	<	-	-	-
V	<	0.002	<	0.001	0.001	<	<	<	<	<
Zn	0.16	0.06	0.043	0.041	0.03	0.028	0.23	<	<	<
Zr	<	<	<	0.003	0.004	<	<	<	<	<

	SB-HP	WC-1	WC-2	WC-3	WC-4	WC-5	WC-6	WC-7	WC-8	WC-9
Depth	Well	43	73	11	24	104	44	116	73	69
Cond.	1080	350	114.6	error	769	598	1024	1220	643	650
Hard	11	123	219	47	391	245	78	108	108	151
T. Alk	263	161	256	333	315	290	314	309	253	274
F. Alk	114	192	267	345	261	270	333	225	255	261
pH	8.10	6.73	6.77	7.69	6.64	7.02	7.40	7.30	6.91	7.09
Temp	15	17.9	17.1	19.5	18.3	16.2	16.8	17.6	13.4	16.3
TDS	590	180	270	530	480	310	530	650	340	290
PCO_2	-2.66	-1.47	-1.32	-1.12	-2.13	-1.53	-1.87	-1.78	-1.48	-1.62
HCO_3	310.2	192.9	306.6	377.4	396.2	347.1	375.1	369.2	303.1	327.9
F	0.32	0.08	0.07	0.71	0.11	0.1	0.34	0.35	0.43	0.29
Cl	177	13	17	67.6	54.3	24	89.2	185	33.6	29.7
N	0.08	<	0.27	0.15	0.14	0.06	<	<	<	<
N	-	<	<	<	<	<	<	<	<	<
SO_4	79.2	17	23.3	265	160	30.7	125	160	86.7	54.1
PO_4	0.006	-	-	-	-	-	-	-	-	-
Al	0.01	0.008	0.017	0.008	0.008	<	0.011	0.009	<	0.008
Sb	<	<	<	<	<	<	<	<	<	<
As	<	<	0.001	0.01	0.001	0.002	0.004	0.006	0.023	0.002
Ba	0.014	0.005	0.001	0.028	0.072	0.01	0.059	0.07	0.042	0.074
Be	<	<	<	<	<	<	<	<	<	<
B	1.07	0.15	0.21	1.43	0.42	0.18	0.86	1.06	0.93	0.66
Cd	<	<	<	<	<	<	<	<	<	<
Ca	3.07	35.6	66.1	15.8	130	74.6	24.4	34.7	35.9	49.6
Cr	<	<	<	<	<	<	0.001	0.015	<	<
Co	<	<	<	<	<	<	<	<	<	<
Cu	<	0.016	0.026	0.005	0.12	0.006	0.001	0.005	0.002	0.005
Fe	0.2	<	<	<	0.08	0.07	<	0.17	1.4	0.75
Pb	<	<	0.001	<	0.001	<	<	<	<	<
Mg	0.8	8.46	13.4	1.85	16.4	14.5	4.19	5.41	4.68	6.7
Mn	0.043	0.011	0.005	0.002	0.31	0.015	0.15	0.24	0.47	0.37
Mo	<	<	0.002	<	<	<	0.021	<	<	0.001
Ni	<	<	<	<	0.002	<	<	0.012	<	<
PO_4	<	0.03	0.05	0.04	<	0.05	0.02	0.06	0.07	0.02
K	1	1.34	1.94	1.9	3.41	1.37	2.27	2.74	2.67	2.82
Se	-	<	<	<	<	<	<	<	<	<
SiO_2	6.2	11	14.3	6.71	9.06	11.2	6.89	8	9.34	7.69
Ag	<	<	<	<	<	<	<	<	<	<
Na	253	16.9	30.8	235	28.8	30.8	218	275	83.8	57.5
Sr	0.14	0.25	0.71	0.52	2.59	0.97	0.58	0.86	1.67	1.78
Te	-	<	<	<	<	<	<	<	<	<
Tl	-	<	<	<	<	<	<	<	<	<
Th	-	<	<	<	<	<	<	<	<	<
Sn	<	<	<	<	<	<	<	<	<	<
Ti	<	<	<	<	<	0.001	<	<	<	<
U	-	<	<	<	<	<	<	<	<	<
V	<	<	<	<	0.002	<	0.002	<	<	<
Zn	2.01	0.13	0.1	0.089	0.16	0.14	0.11	0.12	0.096	0.13
Zr	<	<	0.002	0.004	<	<	0.001	0.001	0.002	0.003

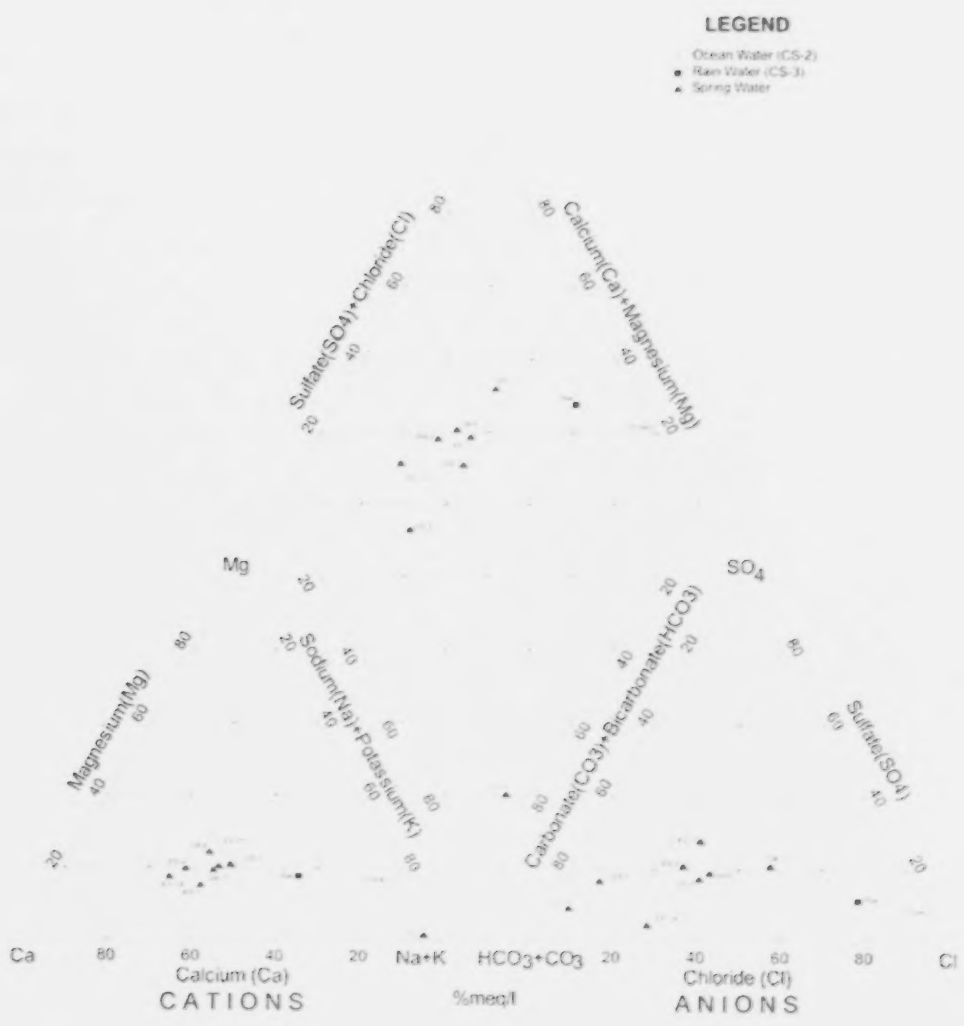
	WC-10	WC-11	WC-12	WC-13	WC-14	WC-15	WC-HP	WC-BP*	WC-S	WC-P
Depth	76	73	73	61	91	46	15	79	Swamp	Pond
Cond	660	686	602	757	710	495	751	2760	105.2	994
Hard	288	62	207	217	176	198	247	88	33	252
T. Alk	300	372	301	310	318	279	228	300	48.5	352
F. Alk	294	342	300	345	309	297	276	301	75	351
pH	6.92	7.95	7.09	7.45	7.29	7.03	7.25	7.69	6.64	7.98
Temp	15.3	21.5	16.9	14.1	15.3	16.1	14.9	18.1	21.1	19.2
TDS	310	350	280	370	350	270	400	1660	60	510
PCO_2	-1.42	-2.33	-1.58	-1.94	-1.75	-1.55	-1.87	-2.20	-1.88	-2.41
HCO_3	359.1	439.5	360.0	369.7	379.9	333.9	272.3	355.4	57.9	412.0
F	0.05	0.11	0.08	0.58	0.41	0.84	0.22	0.15	<	1.1
Cl	29.2	17.3	20.6	11.8	15	10.1	20.3	29.7	8	78.8
N	0.86	<	<	<	0.07	<	0.07	0.08	<	<
N	<	<	<	<	<	<	<	<	<	<
SO_4	33.3	22.9	24.2	128	93.7	25	210	27.9	1.0	113
PO_4	-	-	-	-	-	-	-	-	-	-
Al	0.007	0.008	0.012	<	<	0.008	0.007	0.012	0.03	0.008
Sb	<	<	<	<	<	<	<	<	<	<
As	<	0.003	0.001	0.018	0.009	0.023	<	0.21	<	0.005
Ba	0.022	0.014	0.047	0.13	0.07	0.14	0.053	0.015	0.013	0.035
Be	<	<	<	<	<	<	<	<	<	<
B	0.14	0.54	0.34	0.77	0.96	0.56	1.25	5.72	0.12	0.41
Cd	<	<	<	<	<	<	<	0.0007	<	<
Ca	93.1	20.2	65.5	76.1	58.4	67.7	81	29.2	9.0	67.7
Cr	<	<	<	<	<	<	<	0.002	<	<
Co	<	<	<	<	<	<	<	<	<	<
Cu	0.025	0.001	0.02	0.001	0.025	<	0.002	0.003	0.005	0.004
Fe	0.08	<	0.05	0.1	<	0.56	0.14	<	0.51	0.06
Pb	<	<	0.001	<	<	<	<	<	<	<
Mg	13.7	2.79	10.8	6.62	7.58	7.2	11.2	3.8	2.66	20.6
Mn	0.042	0.069	0.018	0.38	0.007	0.57	0.21	0.006	0.082	0.12
Mo	<	<	<	<	<	<	0.002	0.003	<	0.002
Ni	0.001	<	0.002	<	<	<	<	0.002	0.001	0.002
PO_4	0.04	0.05	0.02	0.04	0.06	0.05	0.03	0.11	0.08	0.04
K	1.95	3.05	4.52	7.06	2.89	3.13	4.53	6.04	0.82	6.39
Se	<	<	<	<	<	<	<	<	<	<
SiO_2	9.66	7.53	9.49	12	9.23	13.9	6.55	6.9	1.68	10.3
Ag	<	<	<	<	<	<	<	<	<	<
Na	16.8	116	36.8	79.1	79.5	46.7	59.4	693	7.5	93.6
Sr	1.34	0.46	1.03	7.11	2.15	8.52	1.59	1.31	0.081	0.61
Te	<	<	<	<	<	<	<	<	<	<
Tl	<	<	<	<	<	<	<	<	<	<
Th	<	<	<	<	<	<	<	<	<	<
Sn	<	<	<	<	<	<	<	<	<	<
Ti	<	<	<	<	<	<	<	<	<	<
U	<	<	<	<	<	<	0.0007	<	<	0.0006
V	<	0.002	<	<	<	<	<	<	<	0.001
Zn	0.12	0.15	0.16	0.1	0.16	0.18	0.45	0.19	0.11	0.11
Zr	<	<	<	0.005	0.002	0.006	0.001	0.005	<	0.003

APPENDIX B

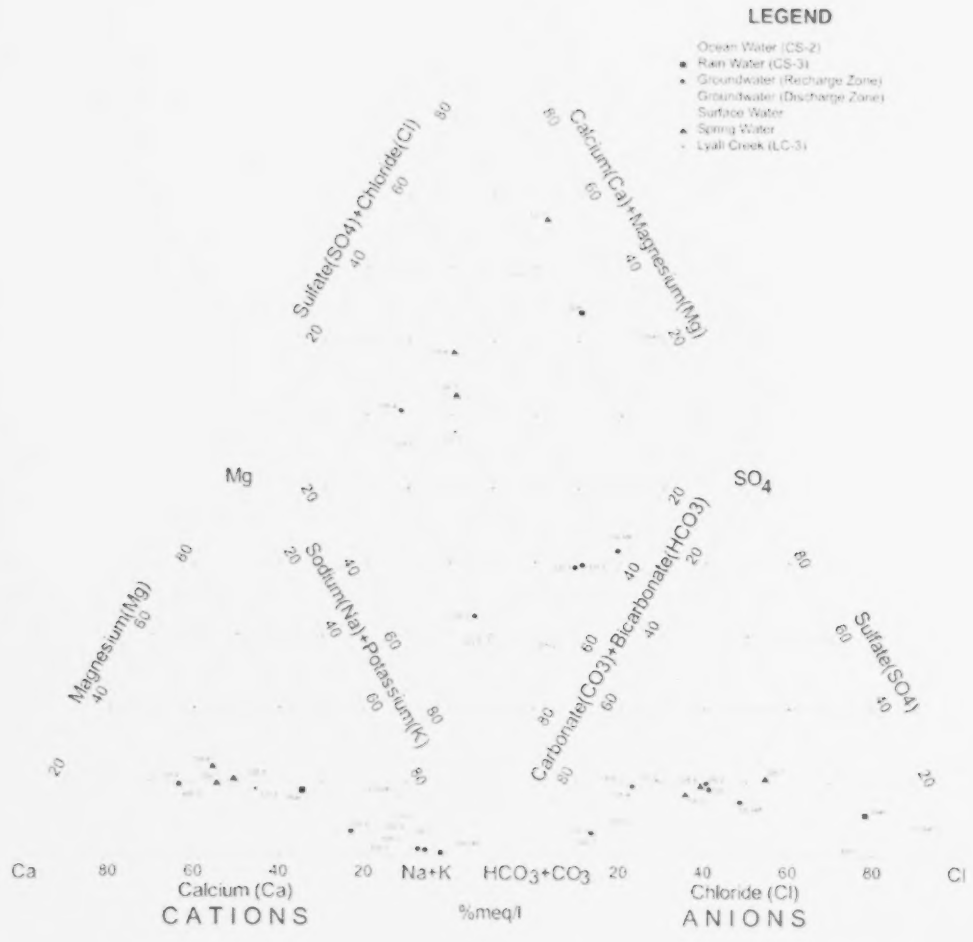
PIPER PLOTS FOR ALL SAMPLE GROUPS



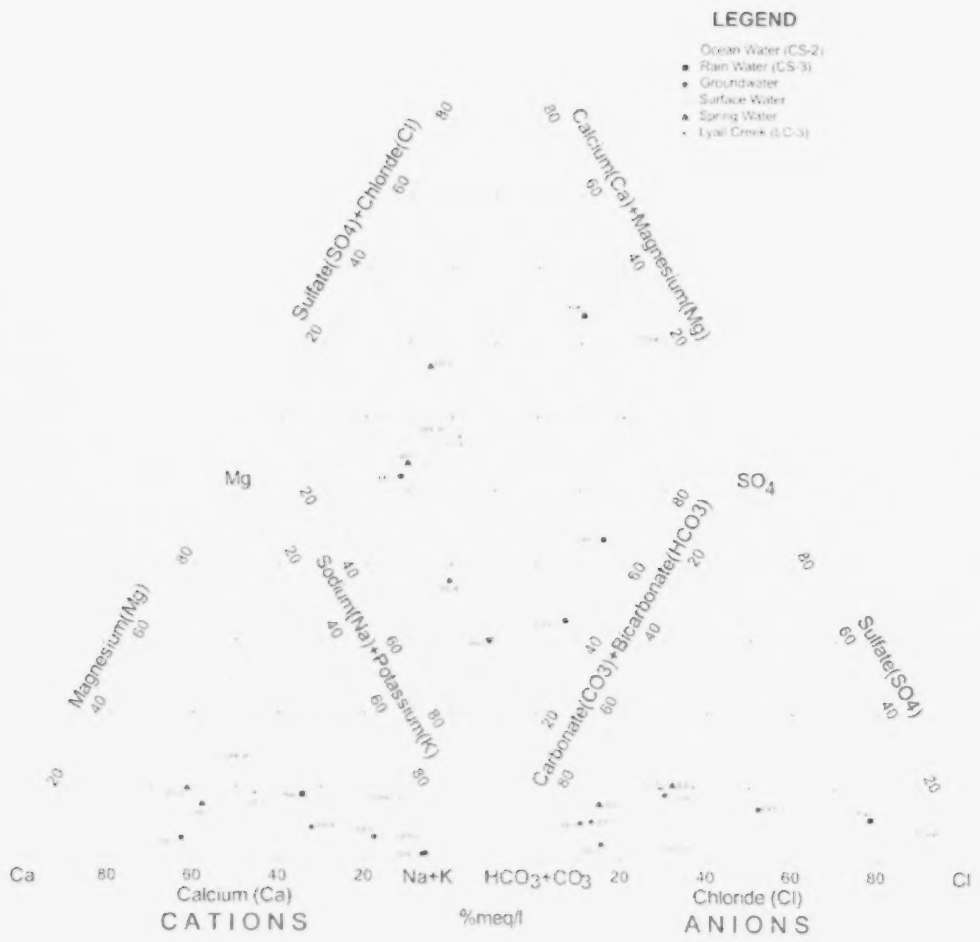
Surface Waters



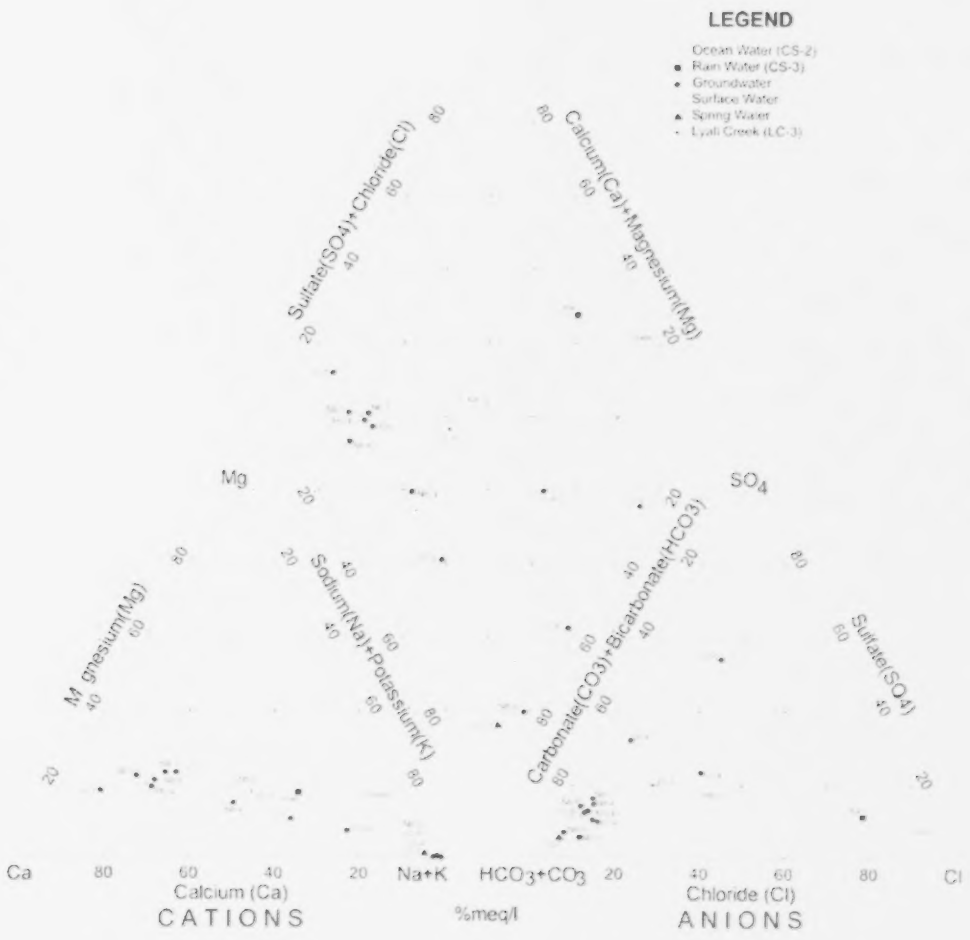
Spring Waters



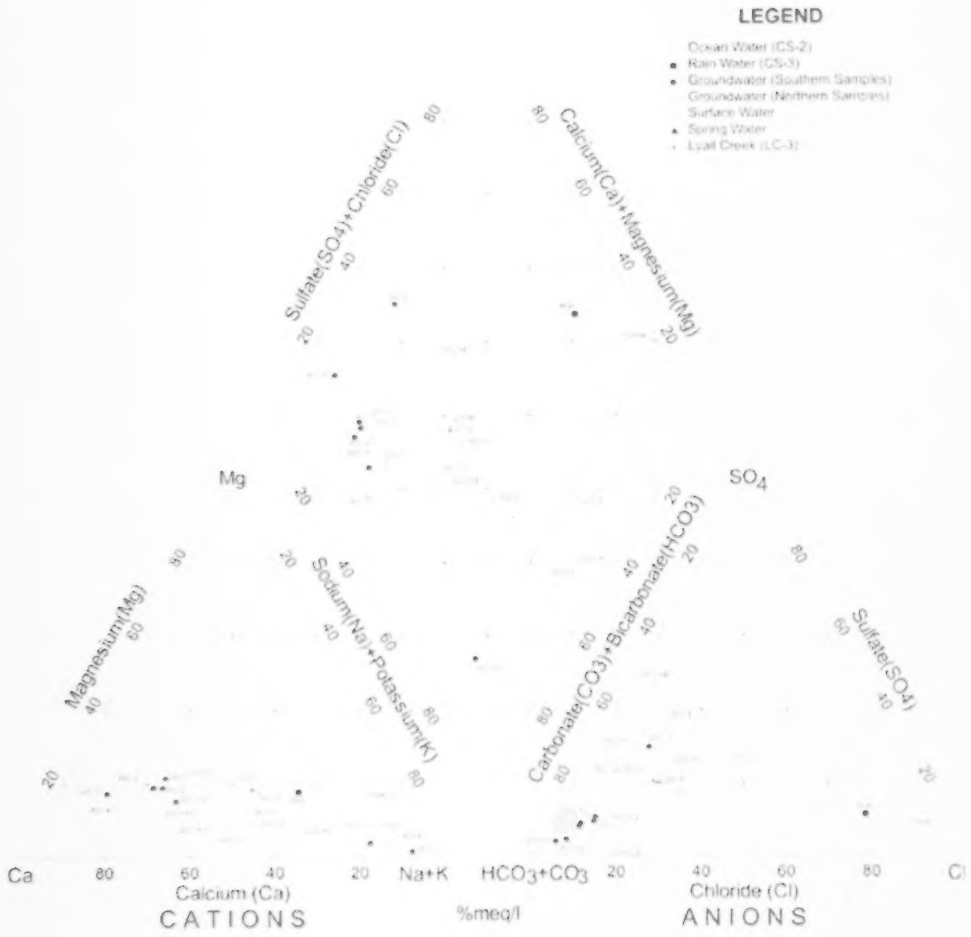
Plumper Sound Flow Region



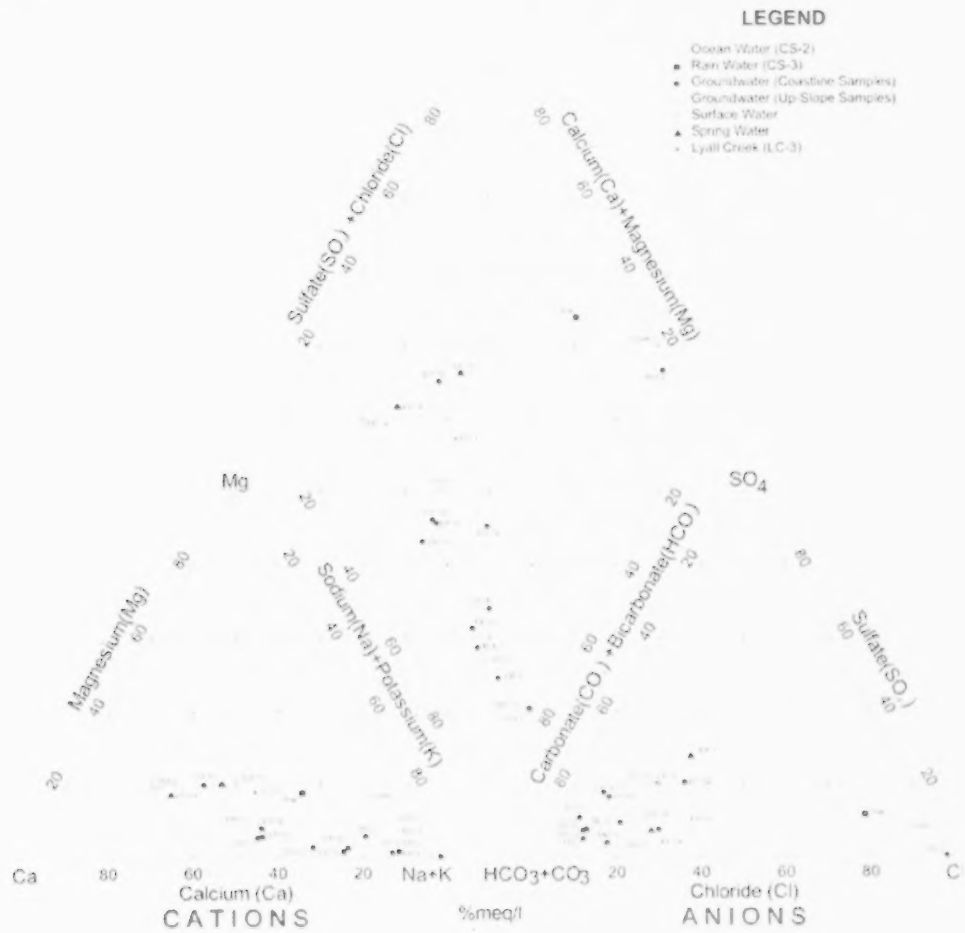
Boot Cove Flow Region



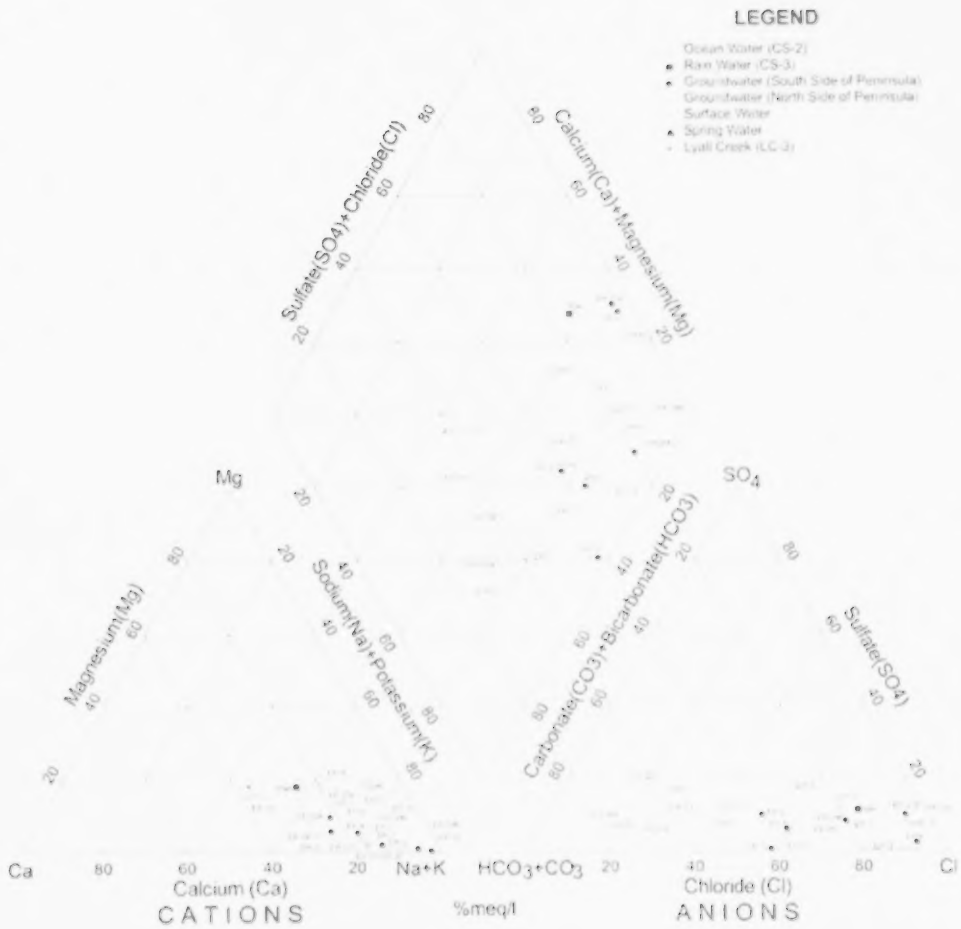
Lyall Harbour Flow Region



Winter Cove Sub-Region



Tumbo Channel Flow Region



East Point Sub-Region

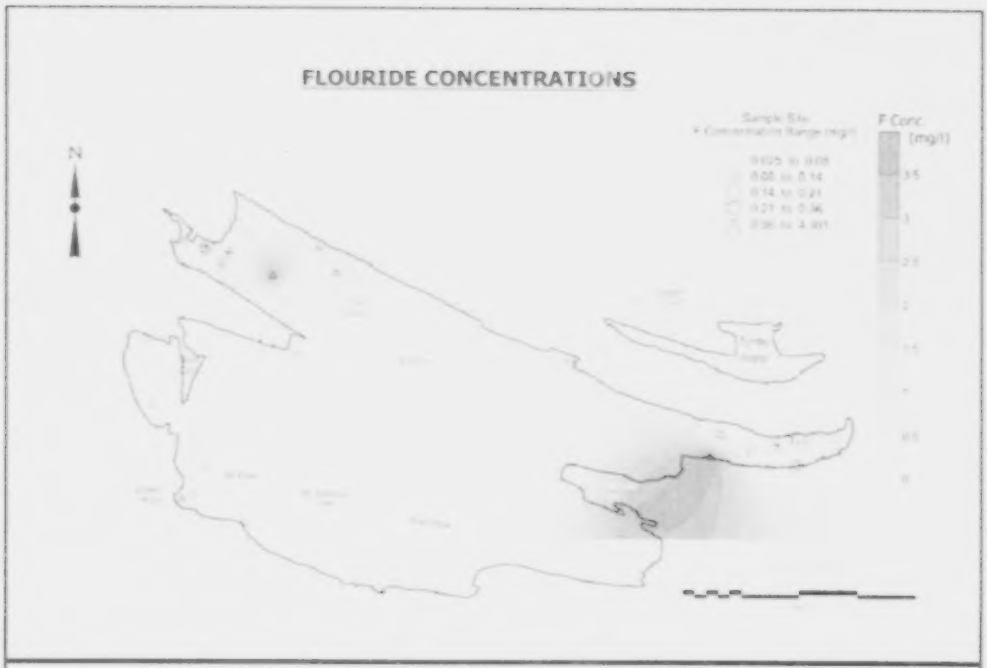
APPENDIX C

CONCENTRATION MAPS

SODIUM CONCENTRATIONS

CHLORIDE CONCENTRATIONS

FLOURIDE CONCENTRATIONS



MANGANESE CONCENTRATIONS